EE 232 Lightwave Devices

Optical Interconnects

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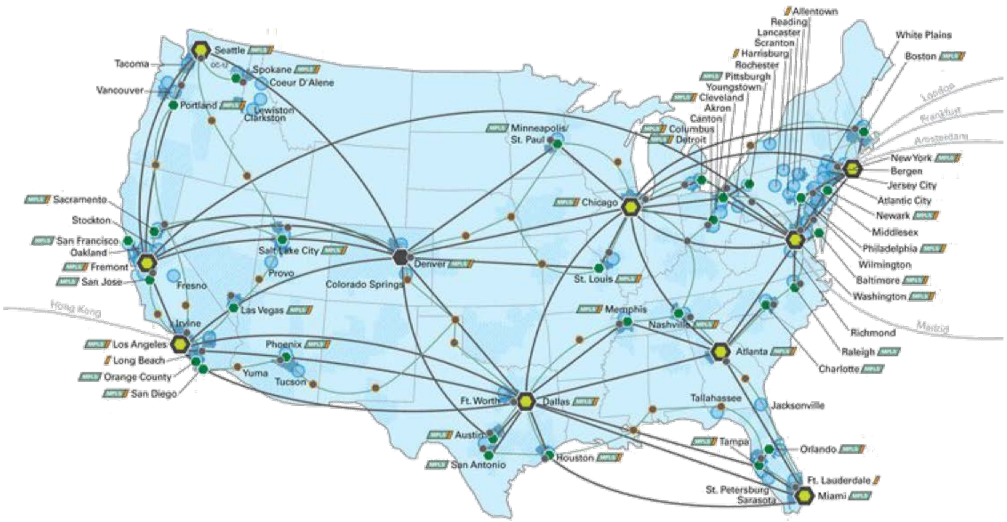
Emergence of Optical Links

US IT Map



Hyper-Scale Data Centers

Inter-continents

inter-datacenter

intra-data center

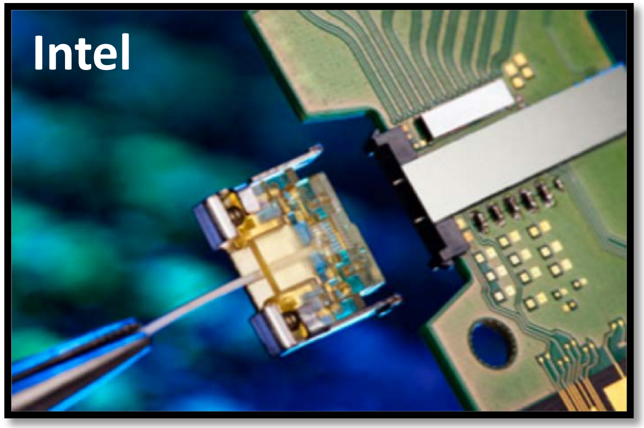
inter-rack

…

Fiber Optics Communication

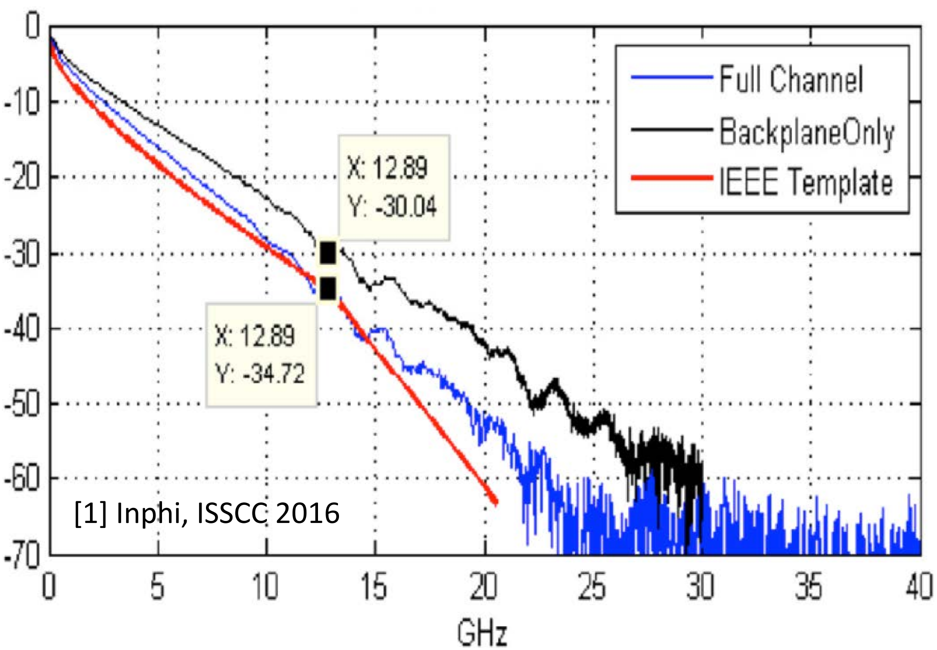
- Low Loss Channel
  - 0.25db/km (@1550nm)
- 1st Fiber optics link
  - Between US, UK and France
  - ~0.3Gb/s
- How to build …
  - » **Low cost**
  - » **Energy-efficient**
  - » **High-speed**

  optical links?!

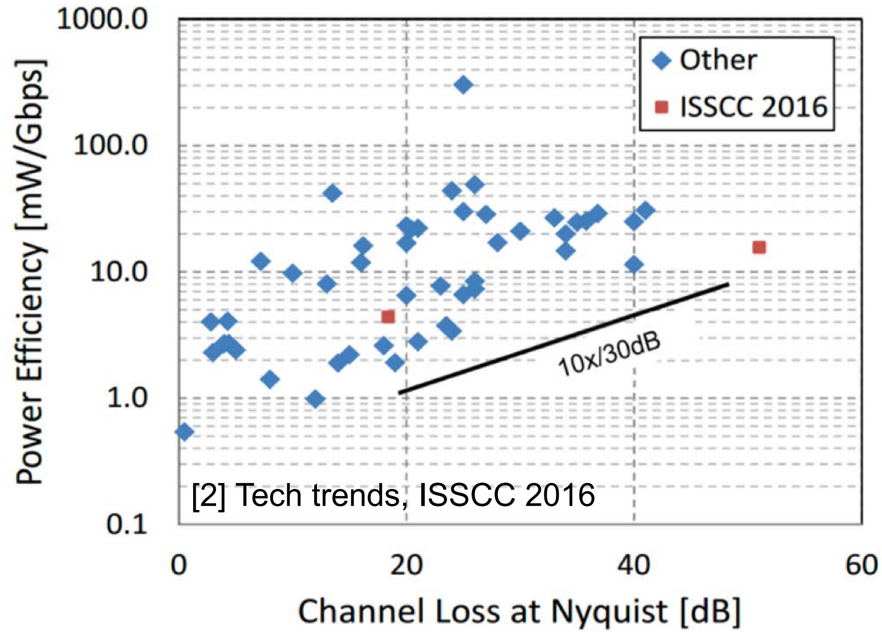


Electrical Links Limitations

Electrical Backplane Channel Loss [1]

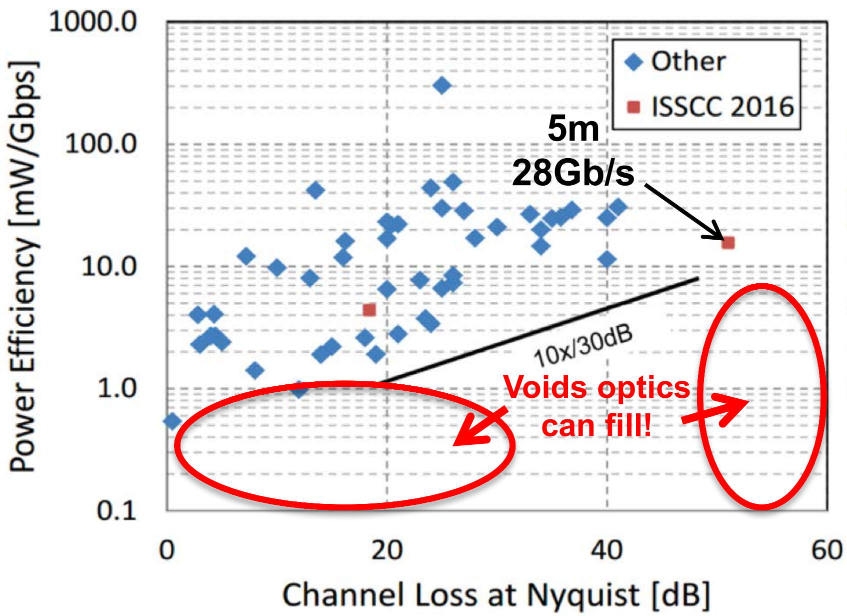


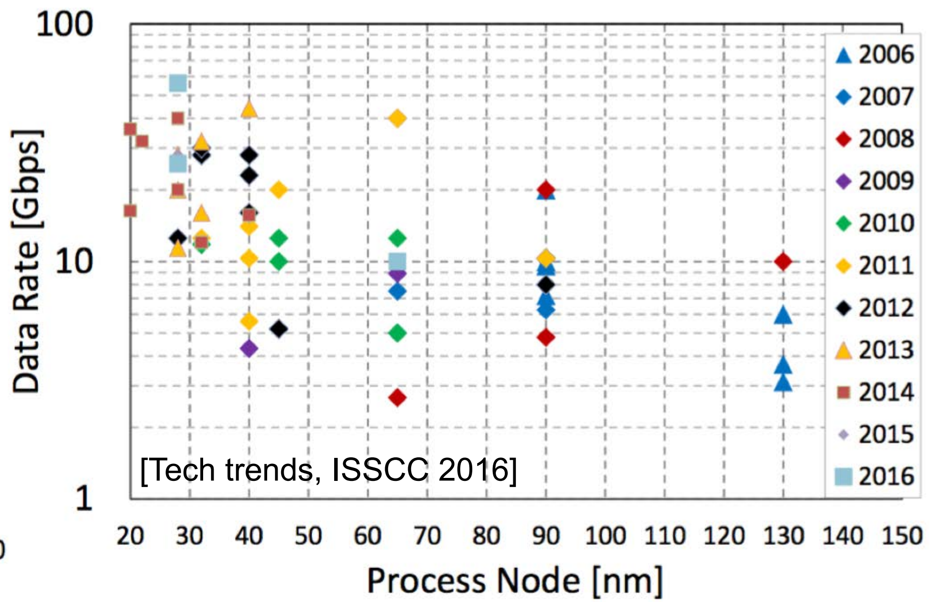
Power Consumption vs. Channel Loss [2]



- High data rate → High channel loss → High transceiver power
- **10 pJ/bit** with -40 dB channel loss at Nyquist frequency

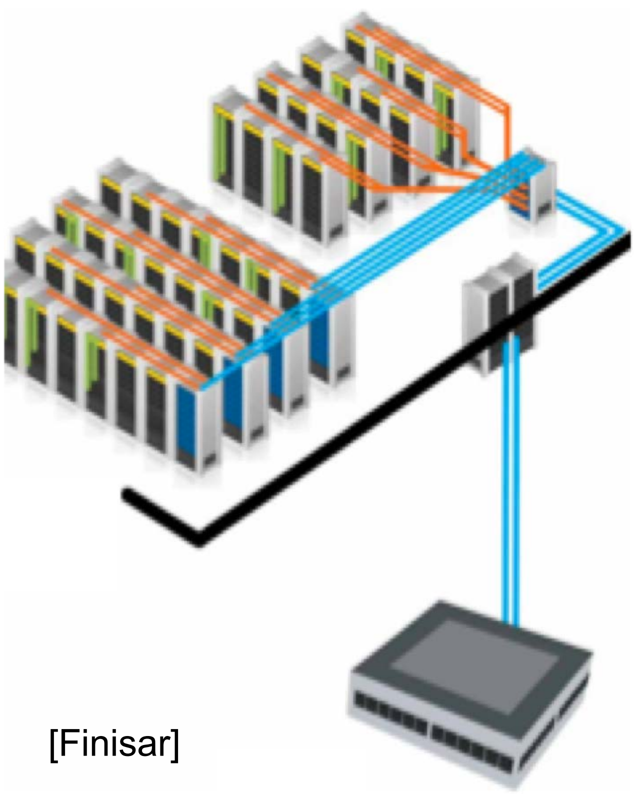
Electrical Links Limitations





- Higher data rates & Longer channels ➔ Higher channel loss
- Moore's law !? …
- **Optical links can break this barrier!**

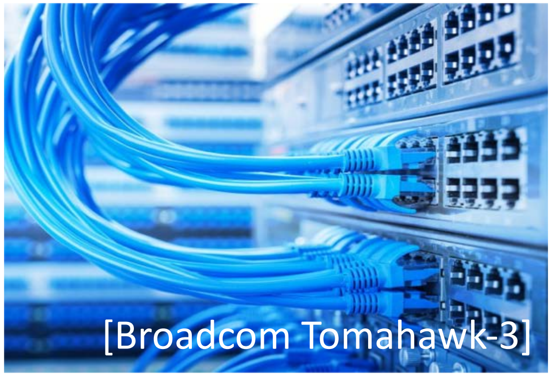
Data Center Interconnects



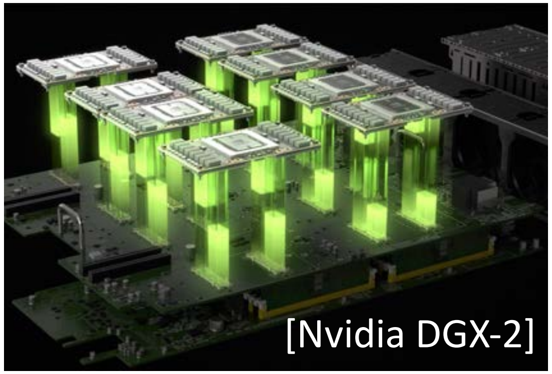
[Finisar]

Long-span Inter-building	40G → 100G → **200G/400G**		
2km/metro	Single-mode Fiber		Optical
Inter-rack	40G → **100G** → **200G/400G**		
20m-2km 1-20 m	Single-mode Fiber Multi-mode Fiber		Optical
Intra-rack	10G → 25G → **56G** → **100G/200G**		
0.5-3 m	Copper Channels		Electrical

Emerging Needs for Photonics

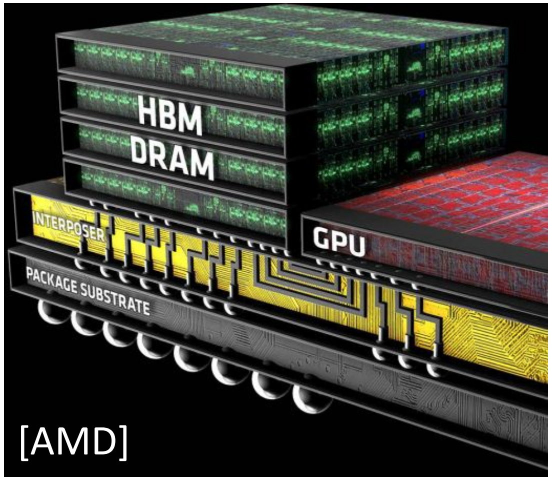


32x400 Gb/s



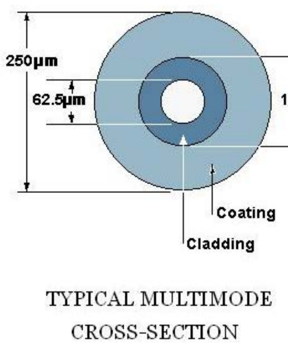
300 GB/s

- **Demand for ultra-high data-rates!**
  - Heterogeneity: HBM, …
  - Advanced integration and packaging
- **Time for photonics to join …**
  - Energy-efficiency & High-bandwidth density

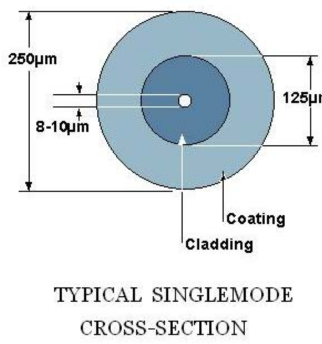


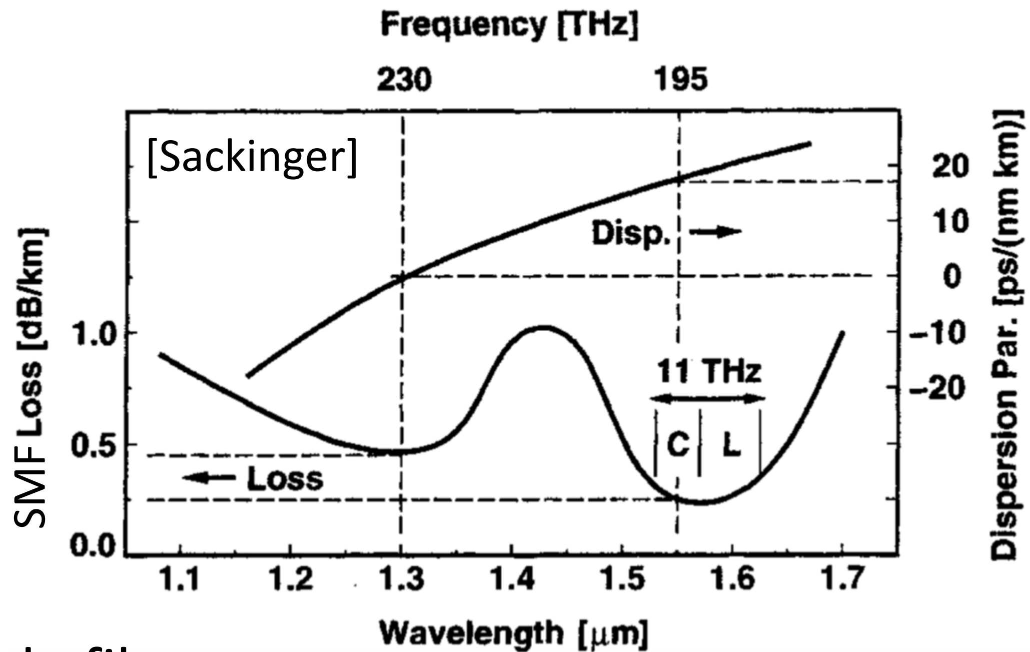
Fiber Optics

Multi-Mode (MMF)



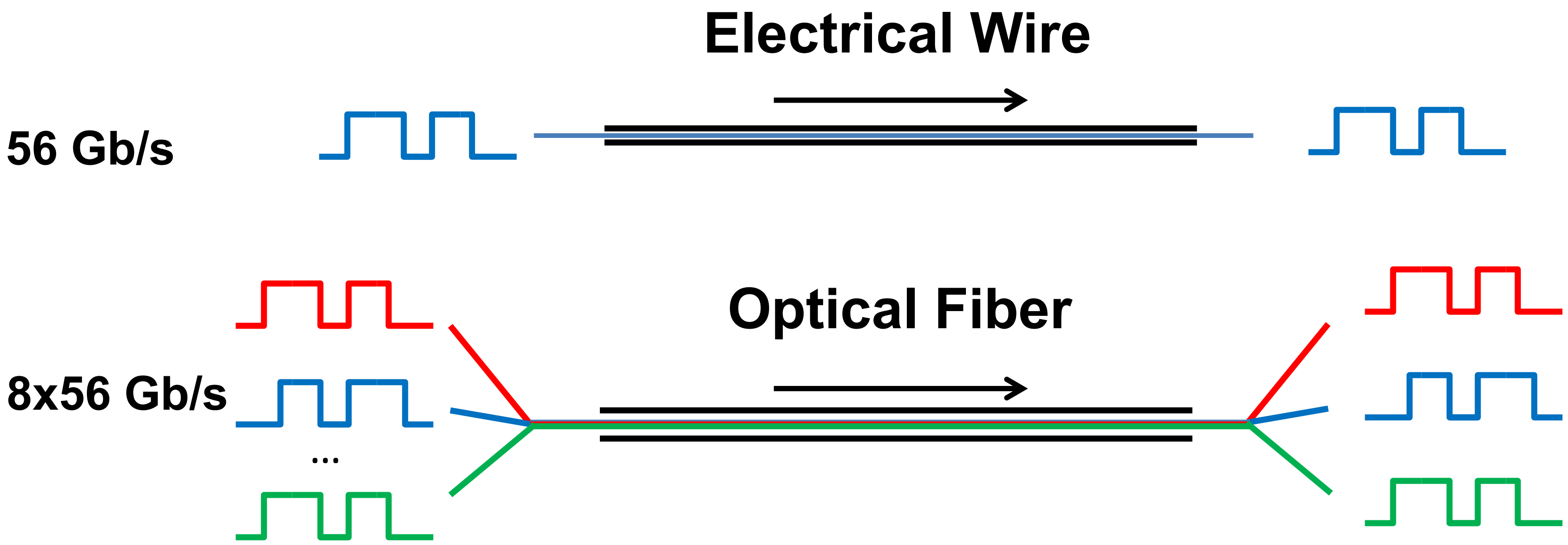
Single-Mode (SMF)





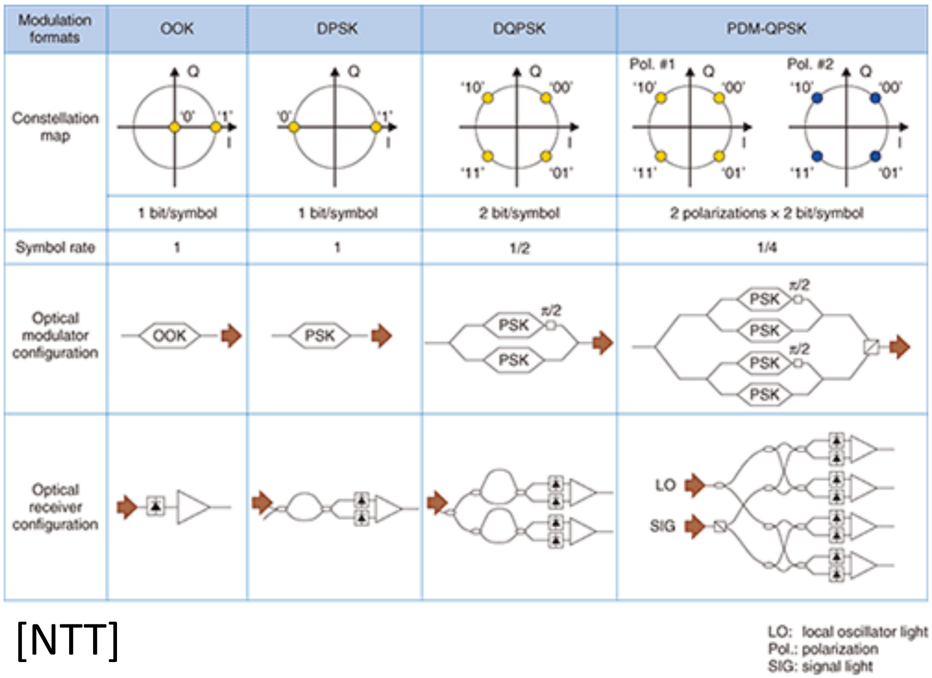
- Multi-mode vs. Single-mode fibers
  - Dispersion, Cost, …
  - MMF for short (< 300m) & SMF for longer distances
- Lowest fiber losses: 1310nm (O-band) & 1550nm (C-band)
  - 1550nm for long-range communication (tele-communication)

Optical Signaling

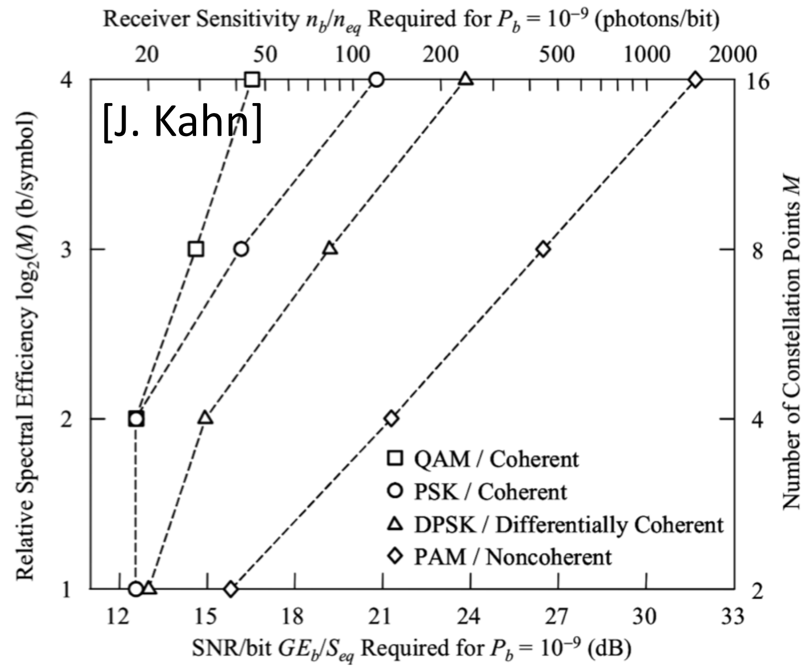


- Wavelength Division Multiplexing (WDM)
  - Boosting aggregate bandwidth per fiber
  - Coarse vs. dense WDM

Modulation Formats



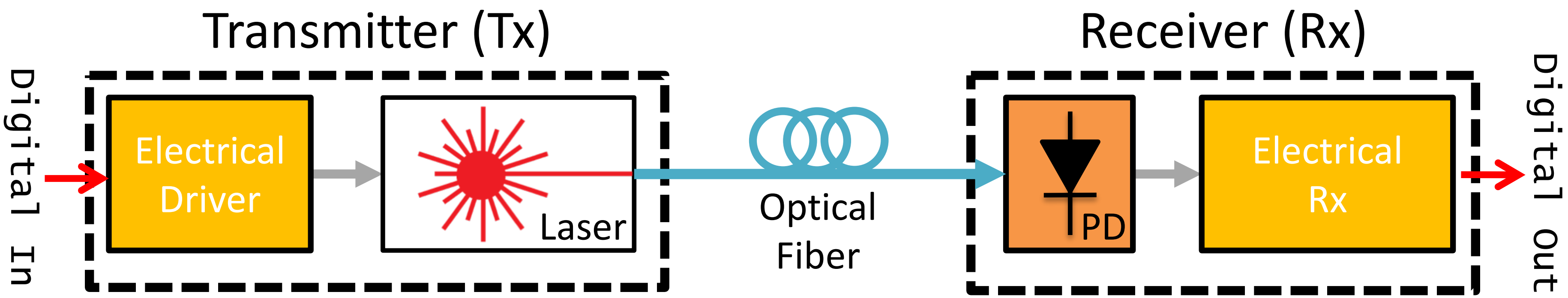
[NTT]



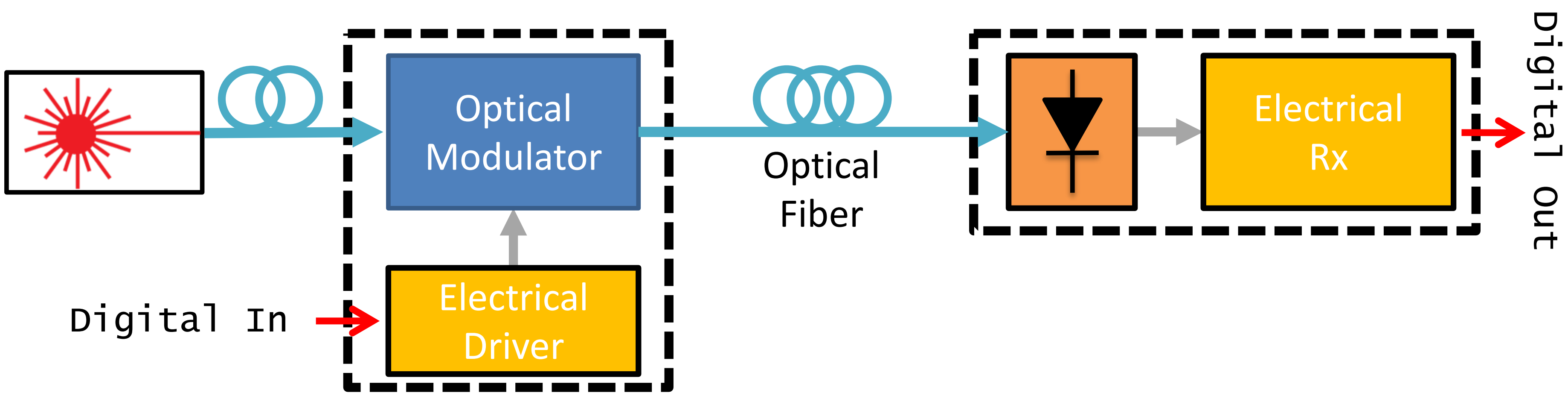
- Higher Order Mod -> Higher Spectral efficiency, but worse SNR
- Direct vs. coherent detection
- Forward error correction (FEC)
- Coherent modulations is used in long-haul, and most of other optical links use pulse amplitude modulation (PAM)

An Optical Link

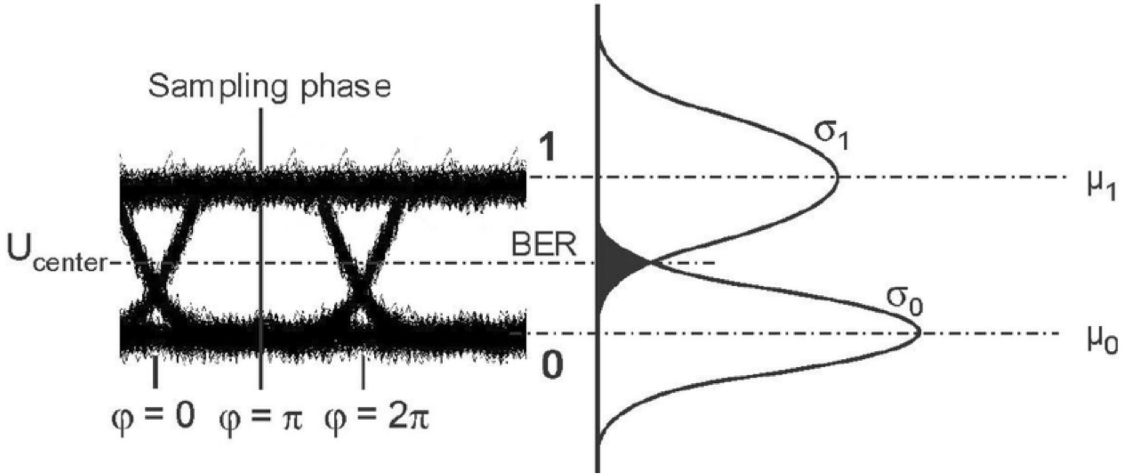
Directly Modulated Laser



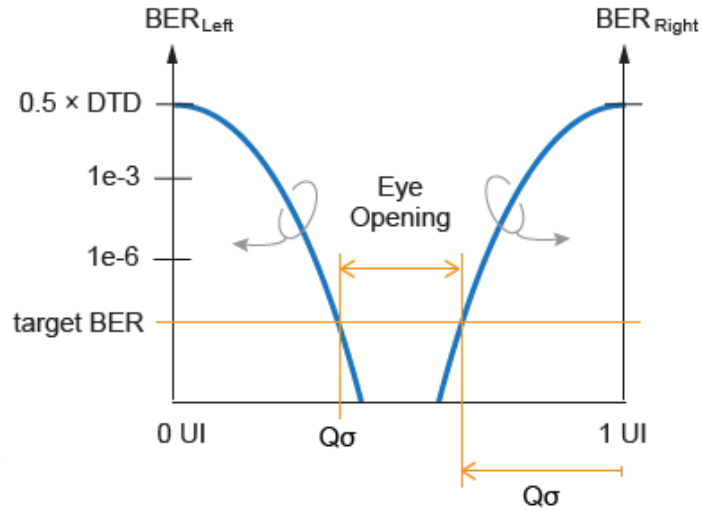
Externally Modulated Laser



Eye-diagram & BER



Tx eye-diagram (NRZ Modulation)



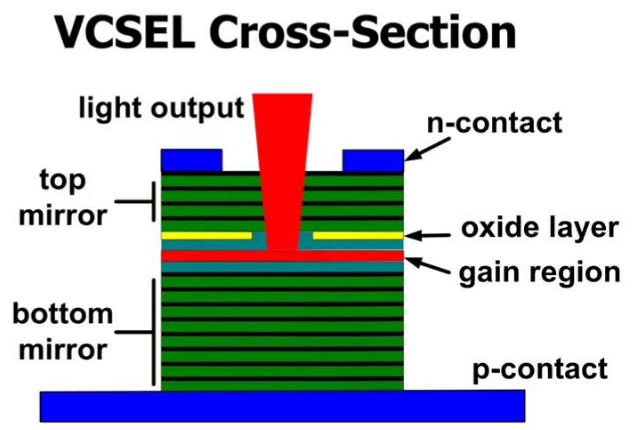
Rx Bathtub curve for BER

- Performance Measures of Tx & Rx
- Tx eye-diagram metrics
  - Extinction Ratio (ER), Insertion loss (IL), Optical Modulation Amplitude (OMA_{TX}), …
- Rx Bathtub curve metrics
  - Bit error rate (BER), H-eye opening, …

Directly Modulated Laser

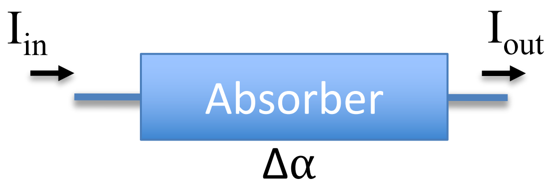
- Requires high relaxation frequency of the laser source
- Challenging packaging & integration
- In research shown up to 50Gb/s
- Most successful case is VCSELs for short-reach links (< 100m)

Vertical Cavity Surface Emitting Laser (VCSEL)

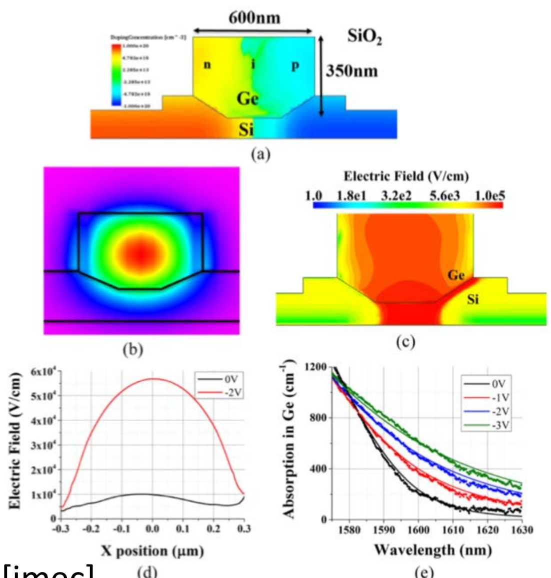


Optical Modulators

Electro-absorption based

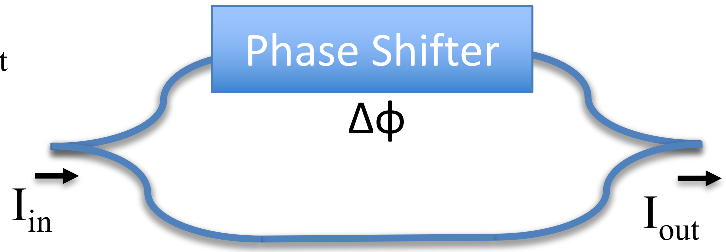


$$I_{out} = I_{in} \times e^{-\Delta\alpha . L}$$

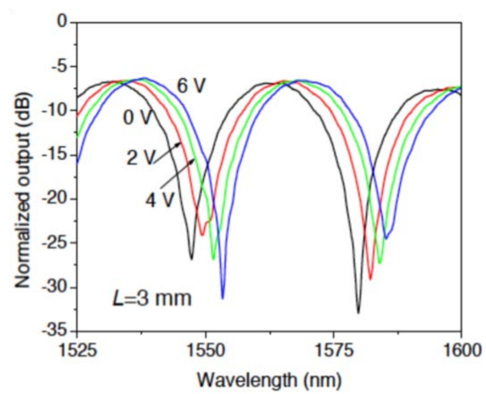


[imec]

Mach-Zehnder Modulator

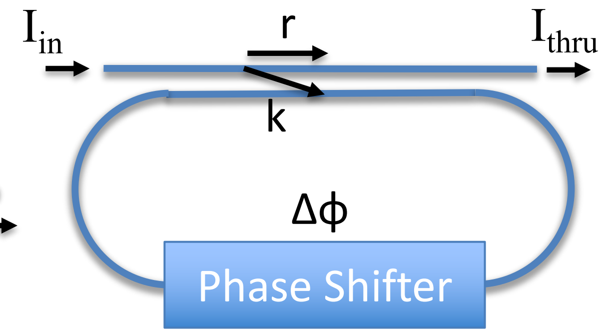


$$I_{out} = I_{in} \times \cos^2 (\Delta\phi/2)$$



[A. Liu]

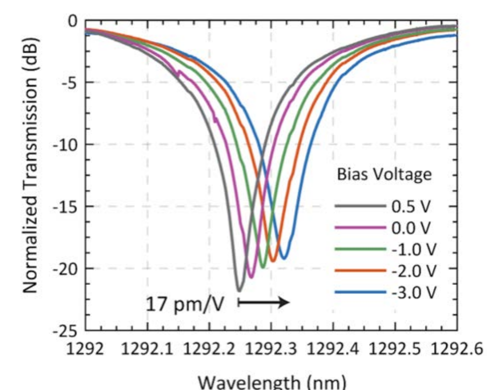
Resonant Modulator



$$\alpha = \frac{I_{thru}}{I_{input}} = \frac{a^2 - 2ar\cos(\phi) + r^2}{1 - 2ar\cos(\phi) + a^2r^2}$$

a = round trip loss

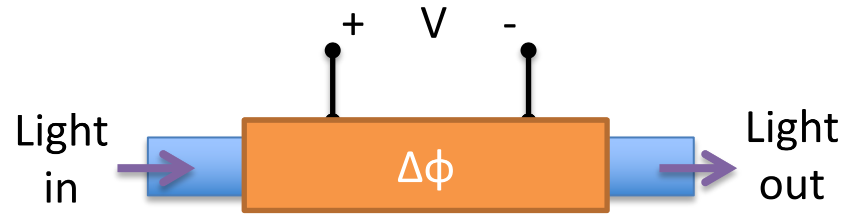
ϕ = round trip phase shift



[A. Atabaki]

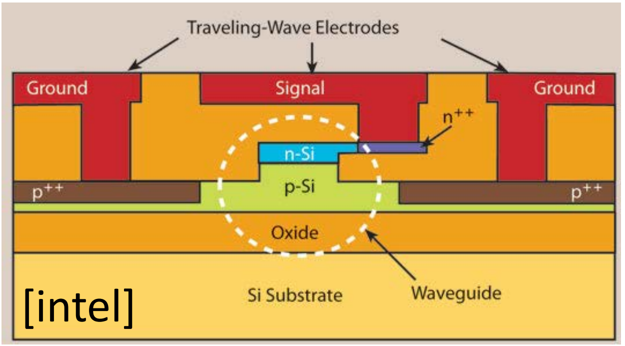
Phase Shifters in Silicon

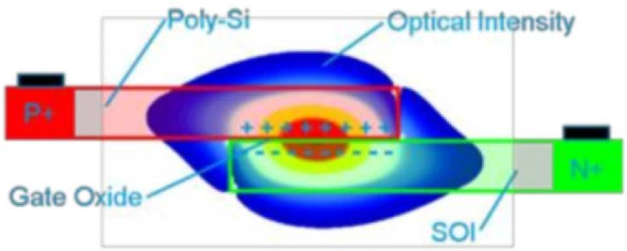
- Pockels effect (not in Si)
- Thermal (efficient but slow ☹)
- Carrier Plasma Effect [Soref]
    - PN-Junction (diodes)
    - SIS-Cap



$$\Delta\phi = \frac{2\pi}{\lambda}\Delta n_{\text{eff}} L$$

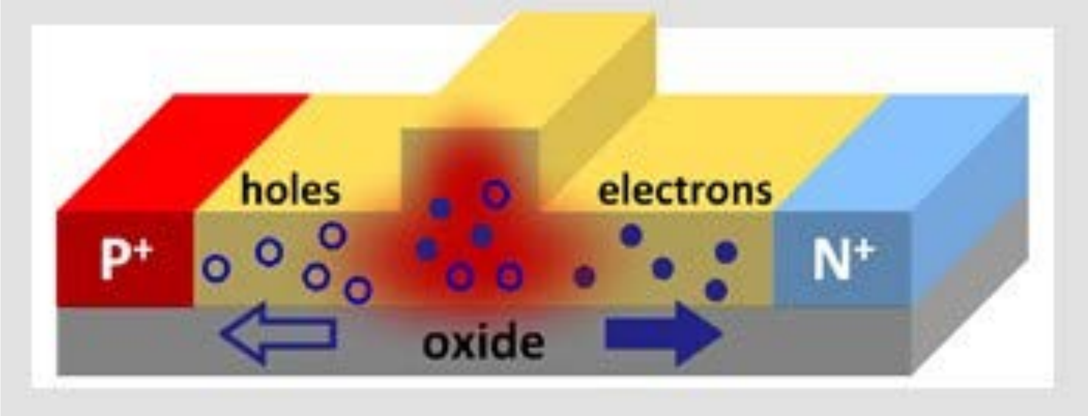
$$\begin{aligned}\Delta n &= \Delta n_e + \Delta n_h \\ &= -8.8 \times 10^{-22}\Delta N_e - 8.5 \times 10^{-18}(\Delta N_h)^{0.8} \\ \Delta\alpha &= \Delta\alpha_e + \Delta\alpha_h \\ &= 8.5 \times 10^{-18}\Delta N_e + 6.0 \times 10^{-18}\Delta N_h\end{aligned}$$





[Cisco]

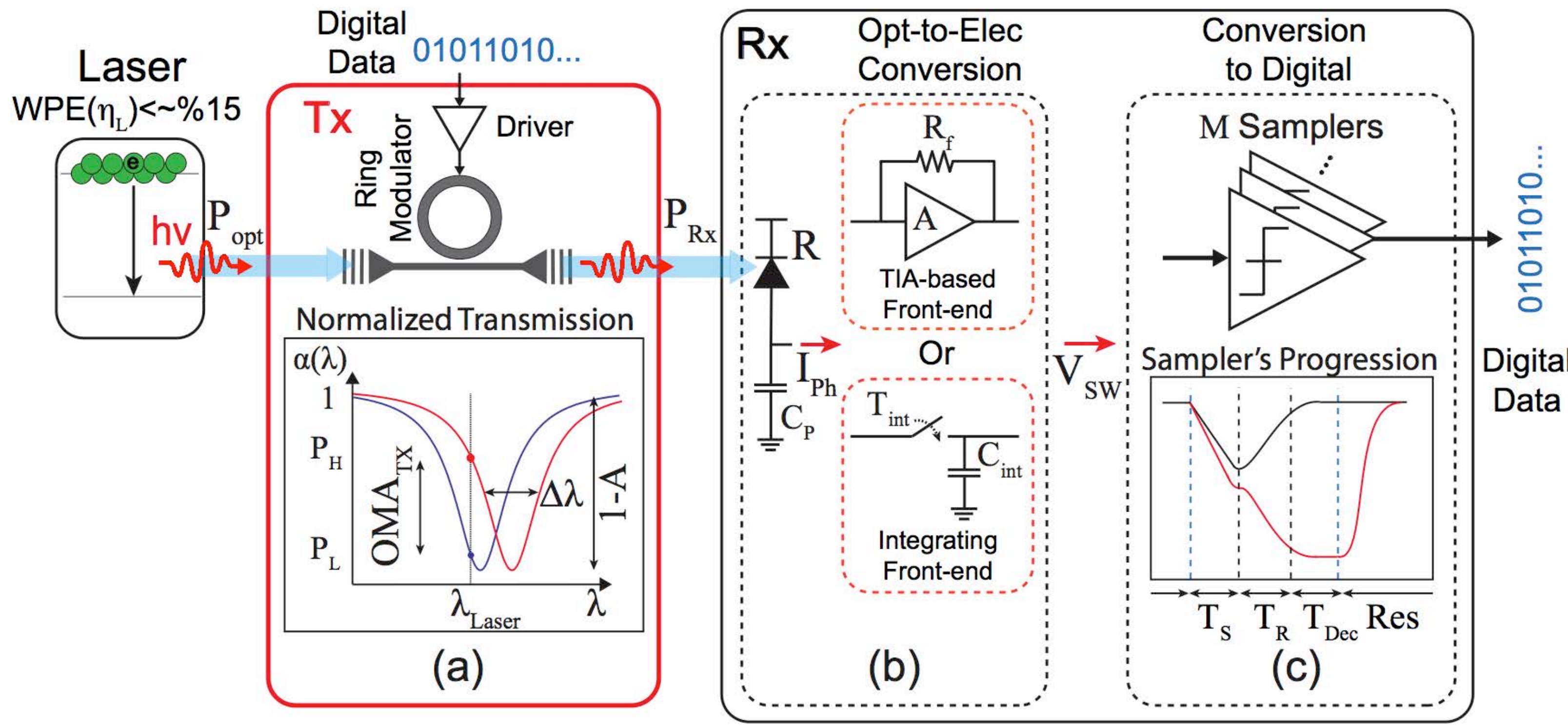
Photodiodes (PD)



[B. Jalali, UCLA]

- PIN & Avalanche Photodiodes
- Optical interconnects mostly use PIN PDs
- Ge for IR light detection
- Metrics: Responsivity, bandwidth, dark current, …

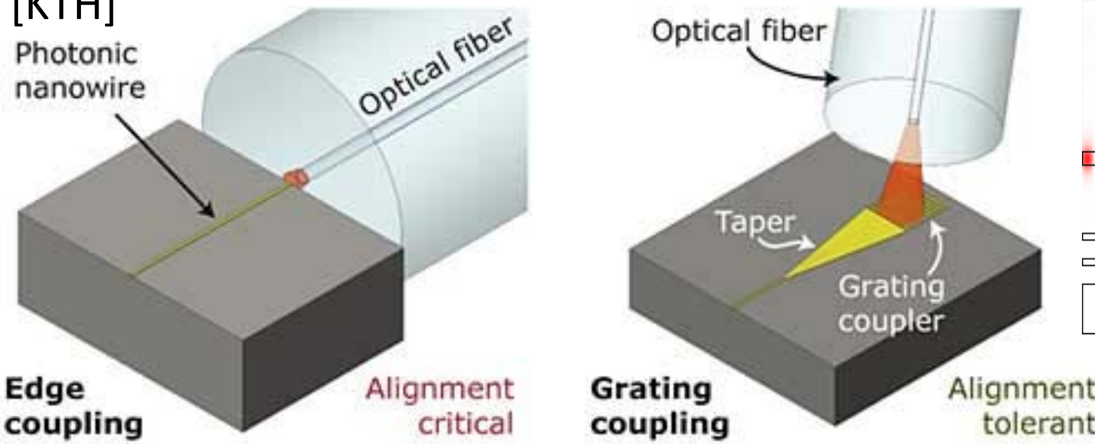
Rx Sub-blocks

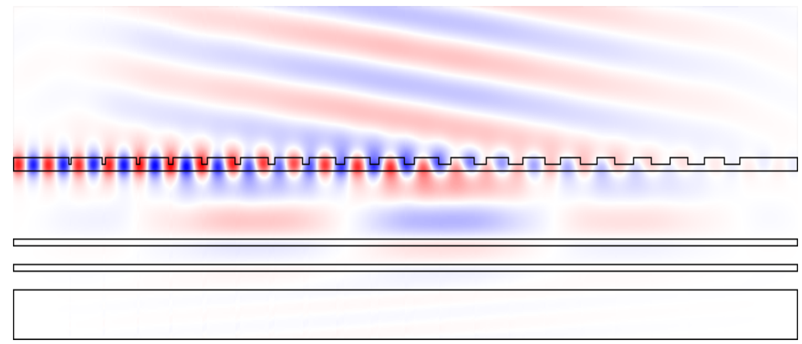


- Receiver sensitivity: Min optical power for a certain data-rate & BER ($P_{Rx,in}$)

Fiber-Chip Interfacing

[KTH]

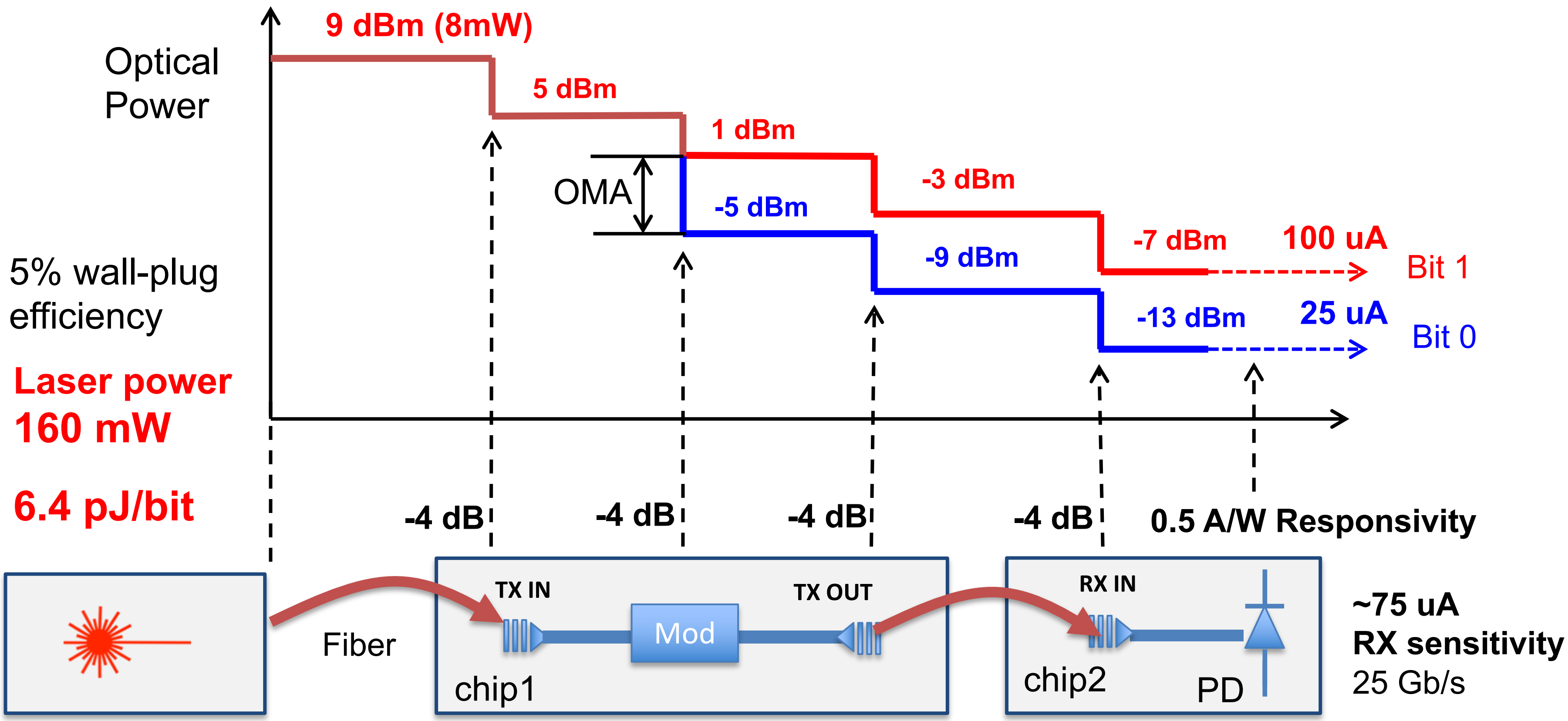




Grating Coupler [Ghent Uni.]

- Loss directly adds to minimum required optical laser power (3x couplers/link in externally modulated laser links)
- Edge vs. Vertical Couplers
- State-of-the-art: 1-2 dB/coupler loss

An example of a Photonic Link Optical Power Breakdown

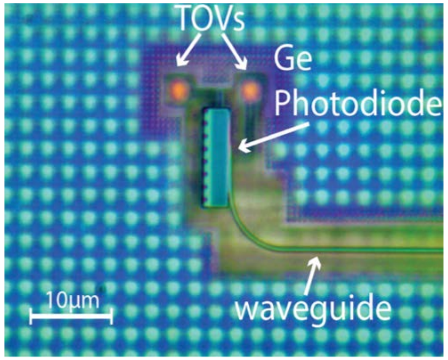


[1] K. Yu, ISSCC 2015 [2] H. Li, ISSCC 2015 [3] C. Sun, JSSC 2016

Photonic Components

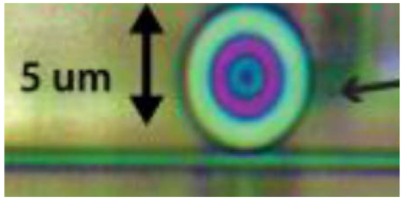
Photodiode

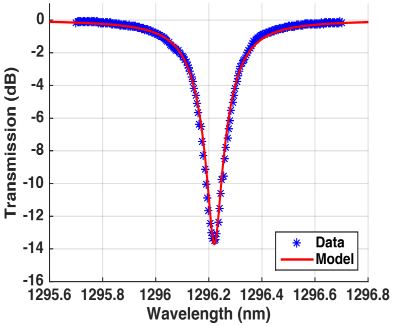
- ❖ High Responsivity ~ 0.8A/W
- ❖ Ge PD show high BW (120GHz) [Vivien]



Modulator

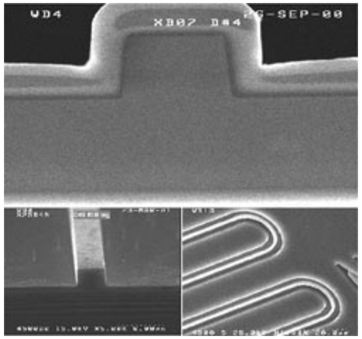
- ❖ High optical bandwidth (~40GHz) allows fast ON/OFF modulation





Waveguides

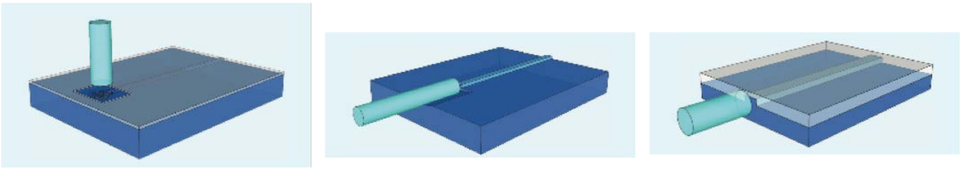
- ❖ Low loss on-chip waveguides ~2dB/cm loss



Intel

Grating Couplers

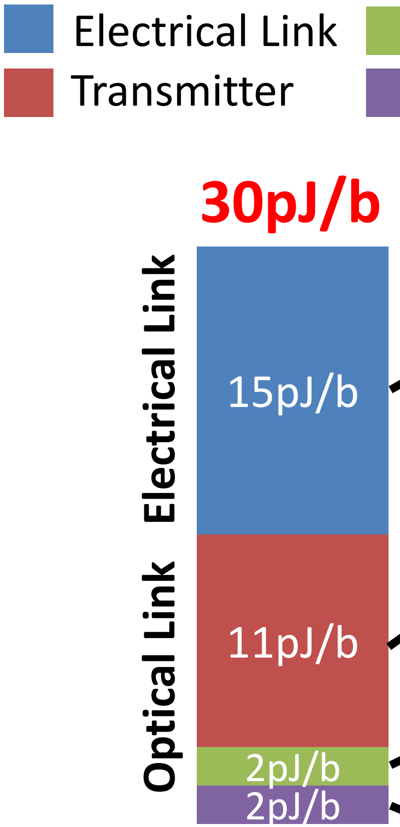
- ❖ Couple light from off-chip to on-chip
- ❖ 1dB/coupler loss



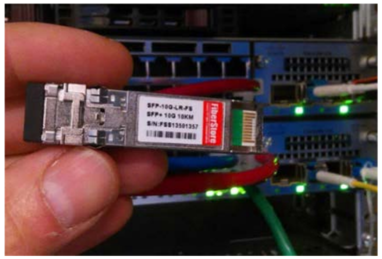
Hochberg

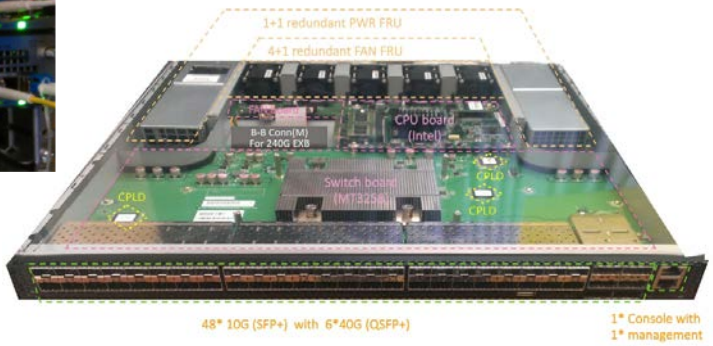
Berkeley
UNIVERSITY OF CALIFORNIA

Energy-efficiency of Photonic Links



Commercial Silicon-Photonic

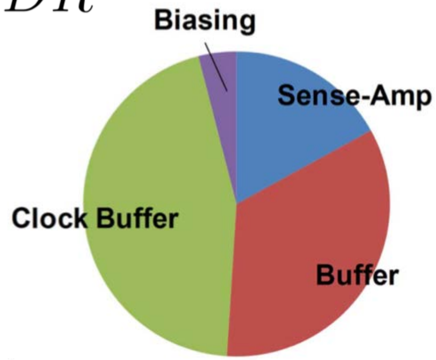




???

$$E_L = \frac{P_{RX,Min}}{\eta_L \cdot \Gamma_L \cdot OMA_{TX} \cdot DR}$$

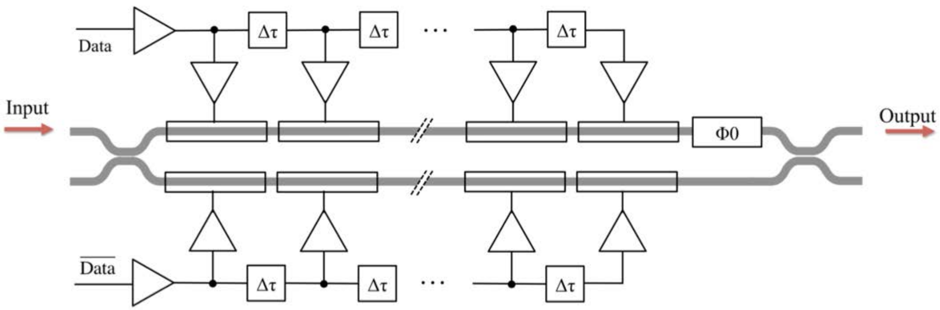
Dominated by electrical blocks (Can be improved by using more advanced CMOS processes)



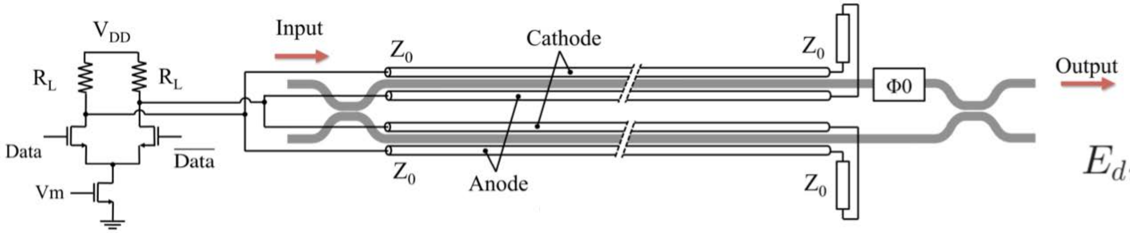
[M. Nazari, JSSC13]

Energy-efficiency of MZMs

- MZM are mm-long devices with pF capacitances to drive!!!
  - Micro-rings are only 20fF ($E=1/4CV_{DD}^2$)
- Parasitic capacitances of the electronic-photonic interconnect also leads to energy-inefficiency



$$E_{dr,MS} = \frac{1}{4\eta_d} V_{dd} \int_{-V_{dd}}^{0} \left(C_m(V) + C_w L \right) dV.$$

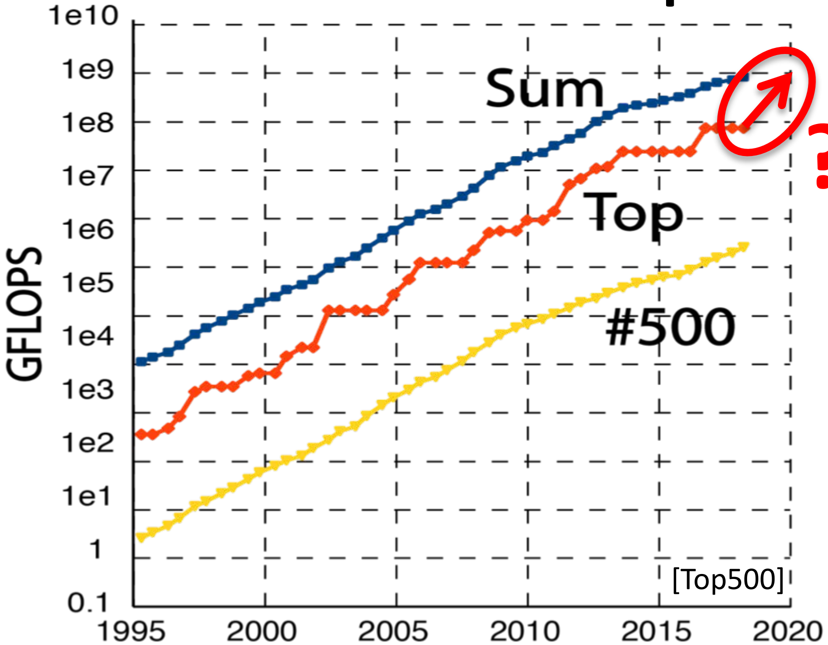


$$E_{dr,TW} = \frac{1}{\eta_d \cdot f_b} \cdot \frac{V_{TW}}{2(Z_0/2)} \cdot V_{DD} = \frac{V_{TW} V_{DD}}{\eta_d Z_0 \cdot f_b}$$

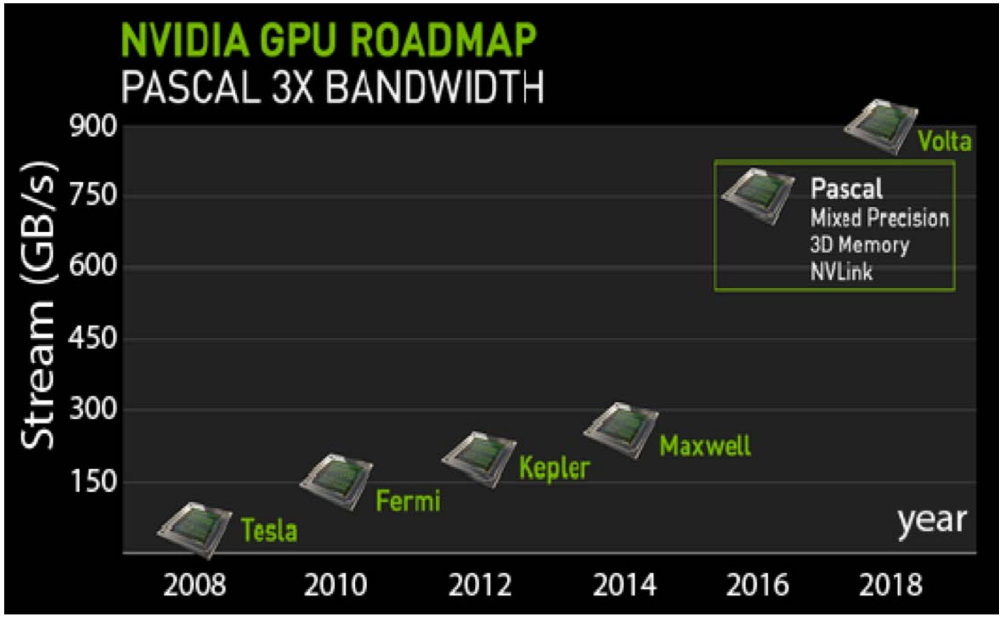
[S. Lin, JLT17]

Energy/Cost Barriers

Exascale HPC Gap



GPU Memory BW Growth



Today's Silicon-Photonic Links: 30pJ/b with $5/Gbps

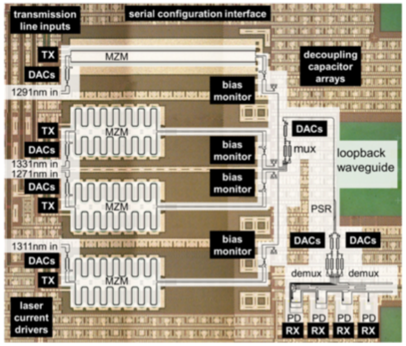
Optical interconnects in an Exascale HPC:

6.8MW power with $200M cost!

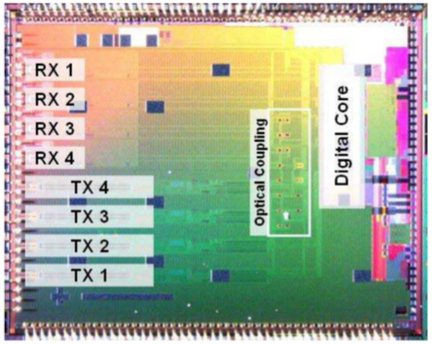
Merging Electronics & Photonic

Integration determines Energy/Cost efficiency!

Monolithic



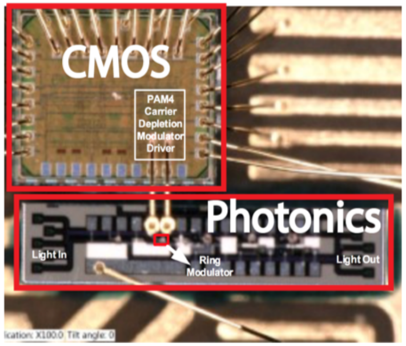
[IBM, OFC 16]



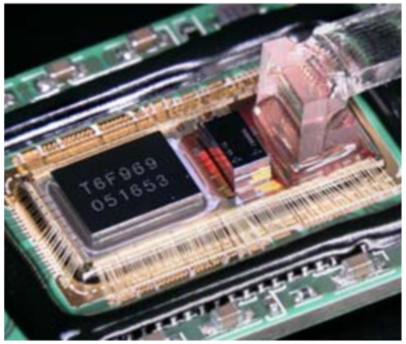
[Luxtera, Hot Chips 09]

- Closest Proximity
- High Interconnect Density
- Low Cost
- Old CMOS

Hybrid / 3D

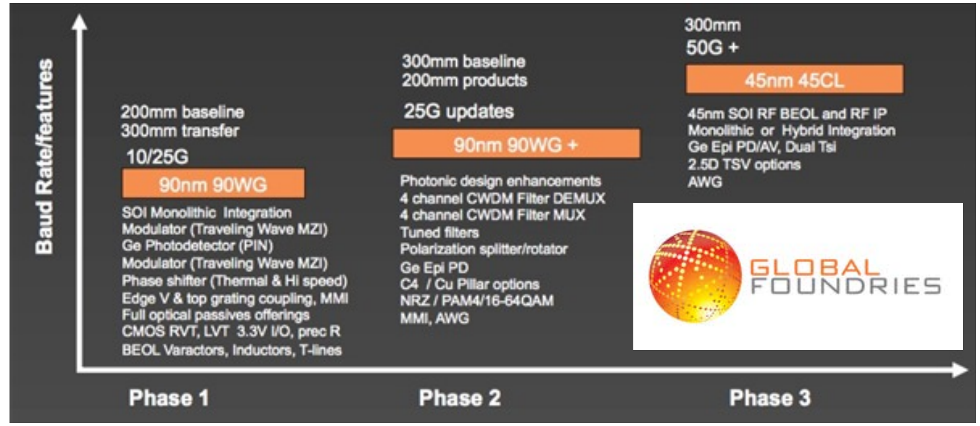


[Roshan-Zamir, OI 16]


[Luxtera, IEDM 17]

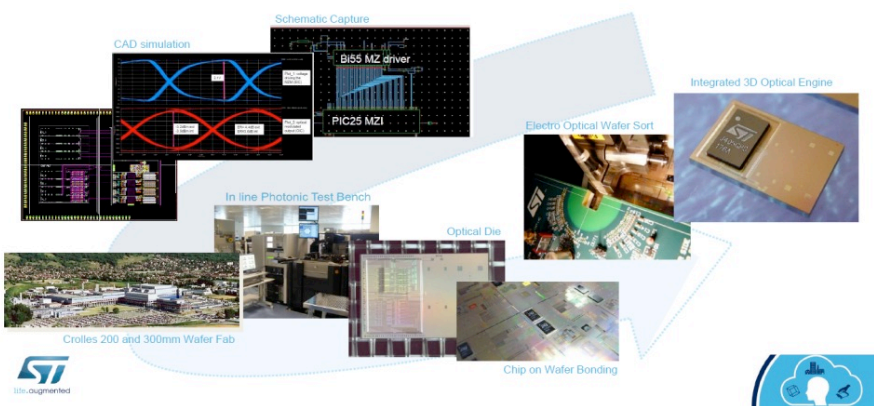
- Large Parasitics
- Low Interconnect Density
- High Cost
- Advanced CMOS

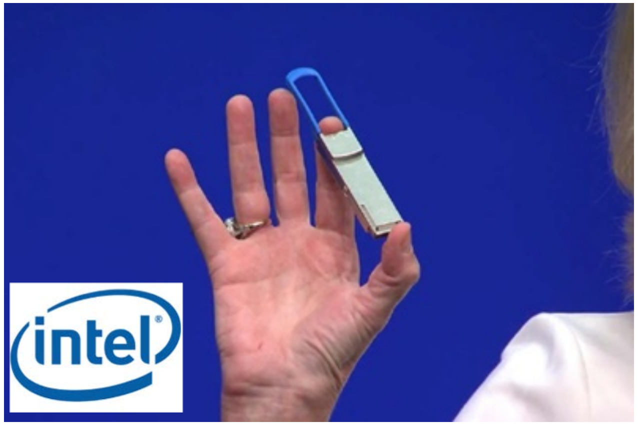
Foundry Movement in Photonics



Silicon-Photonics emerged as a viable solution

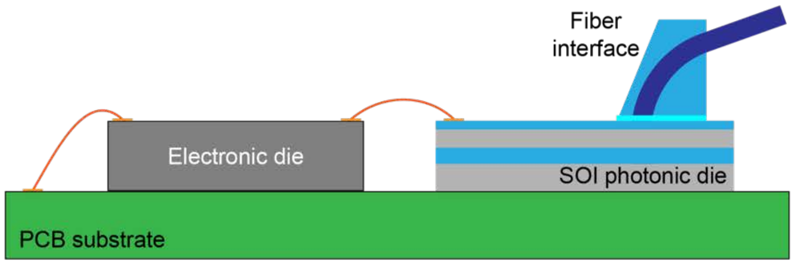
Major foundries now have Silicon-Photonic processes





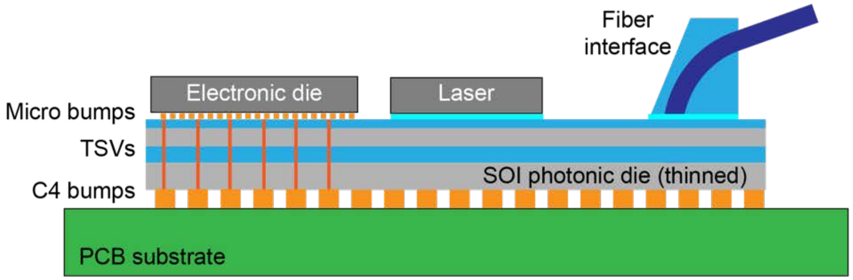
Hybrid/3D Integrations

Wire-bonding



(a)

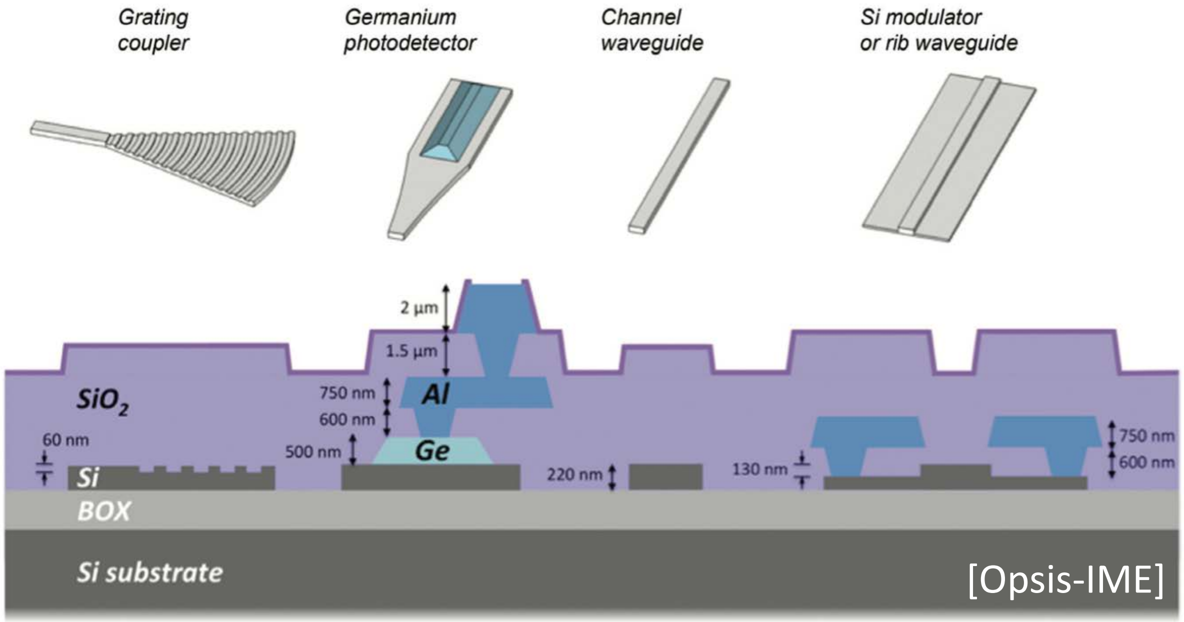
Cu-Pillar [Luxtera]



(b)

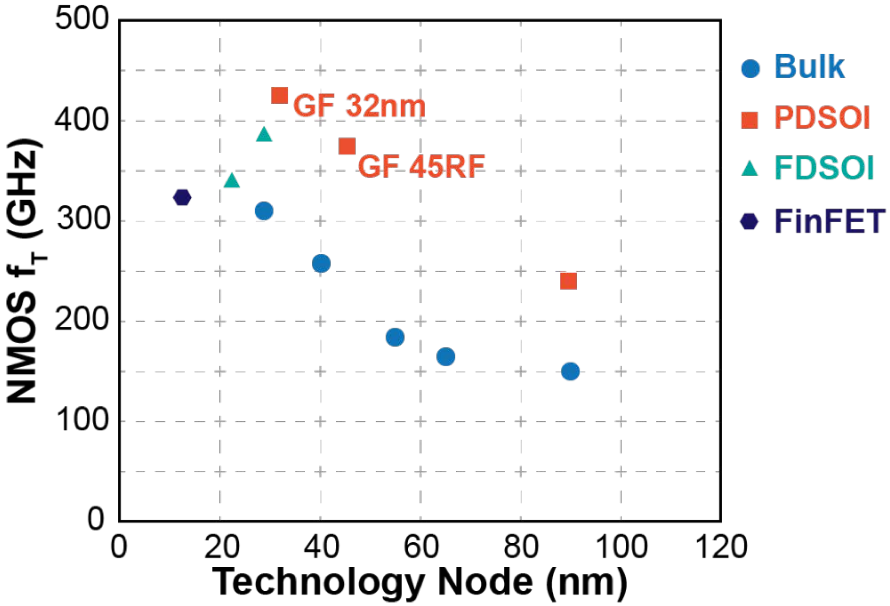
- An integration solution should address:
  - Electro-photonic interconnect
  - Electrical chip signaling
  - Laser & fiber assembly
  - Thermal & Mechanical Stability
- Parasitic capacitance affects both Energy-efficiency of Tx & Sensitivity of Rx

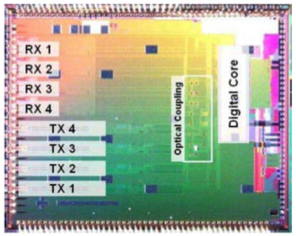
Photonic SOI Processes



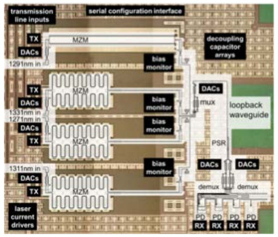
- SOI: Silicon-on-insulator
  - 220nm Crystalline Si + 1.5um Buried Oxide (BOX)
- Partial Etch on Si for patterning Grating Couplers
- Epitaxially grown Ge for photo-detection

Monolithic Silicon Photonics

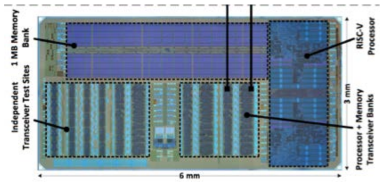




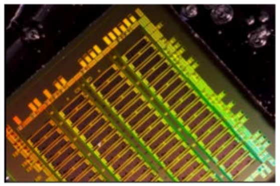
130nm SOI
[Luxtera, Hot Chips 09]



90nm SOI
[IBM, OFC 16]



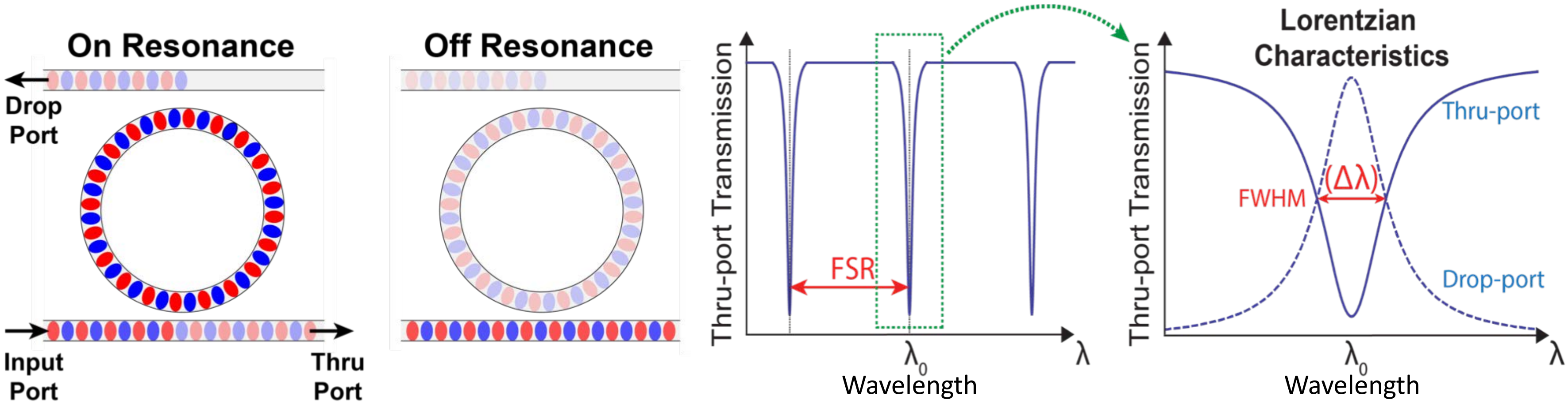
45nm SOI (Zero-change)
[C. Sun, Nature 15]



65nm bulk
[A. Atabaki, Nature 18]

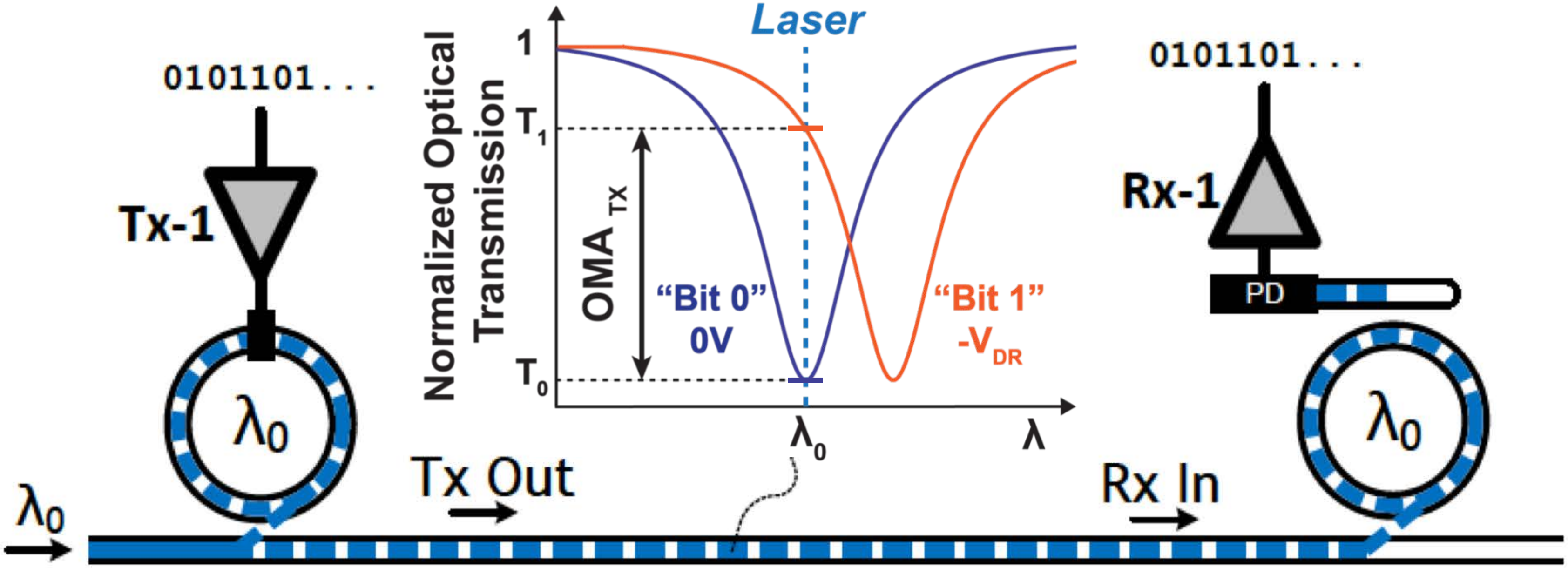
- f_T: Transistors' current gain unity frequency
- f_T affects speed, energy-efficiency, sensitivity, …
- Advanced transistors sensitivity to process change

Micro-ring Modulator (MRM)



- Resonance wavelength: $\lambda_0 = n_{eff} L/m$, m = 1,2,3,...
  - Q-factor: $Q = \lambda_0 / \Delta\lambda$
  - Free spectral range: $FSR = \lambda^2 / n_g L$
- Compact device (radius of 5μm)
  - Energy & area efficient modulator/filter

MRM based Optical Links



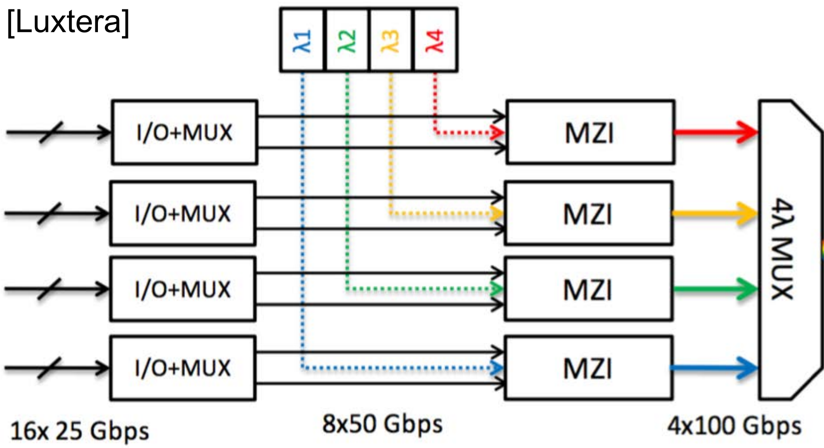
[Courtesy of C. Sun]

Minimum OMA Required ($P_{Rx,in}$)

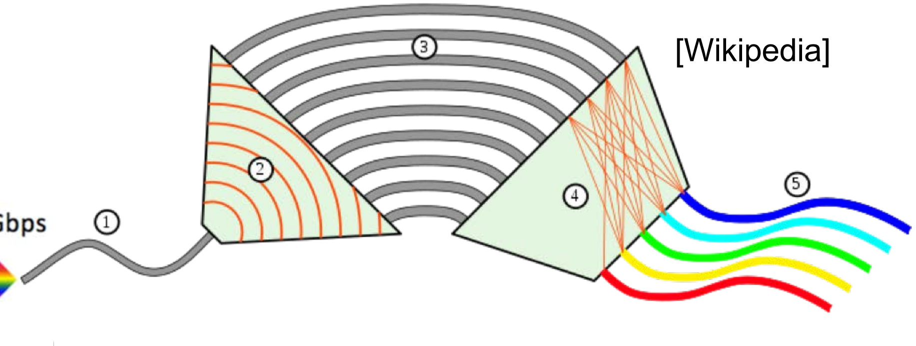
- Modulation Scheme:
  1. Deplete/Inject carriers using PN junctions
  2. Δfree carriers → Δindex of refraction [Carrier-Plasma Effect]
  3. On-Off Keying (OOK) modulation

  *. **OMA**: Optical Modulation Amplitude

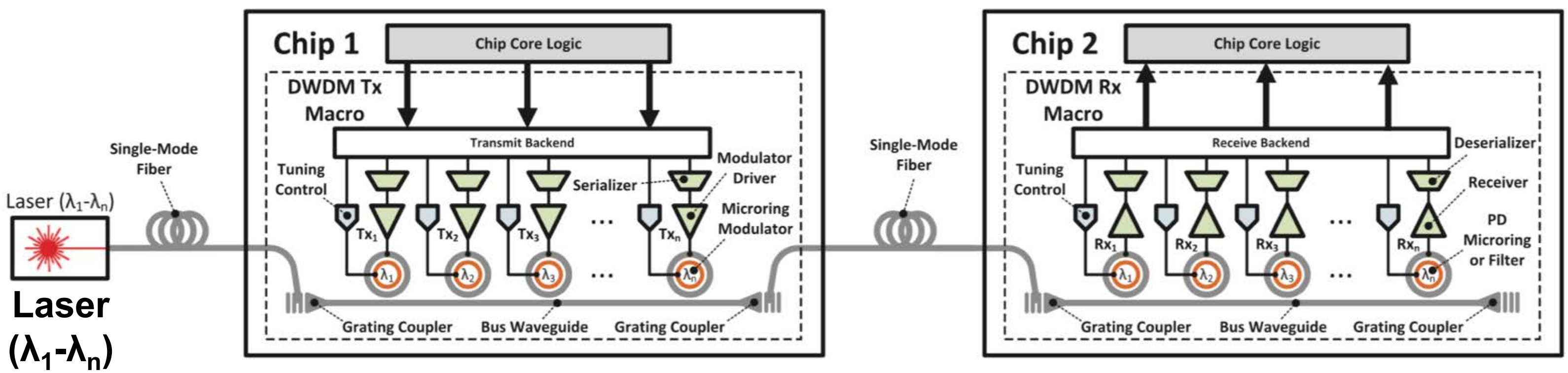
WDM in Practice



MZM + AWG MUX



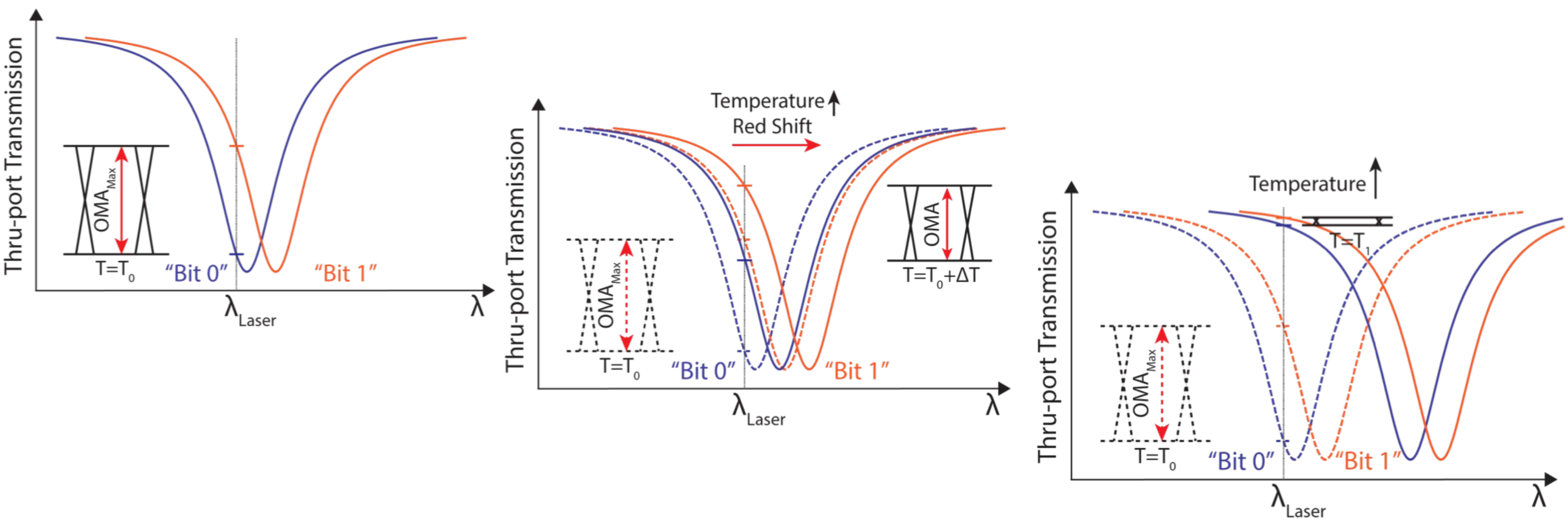
Arrayed Waveguide Grating (AWG) DeMUX



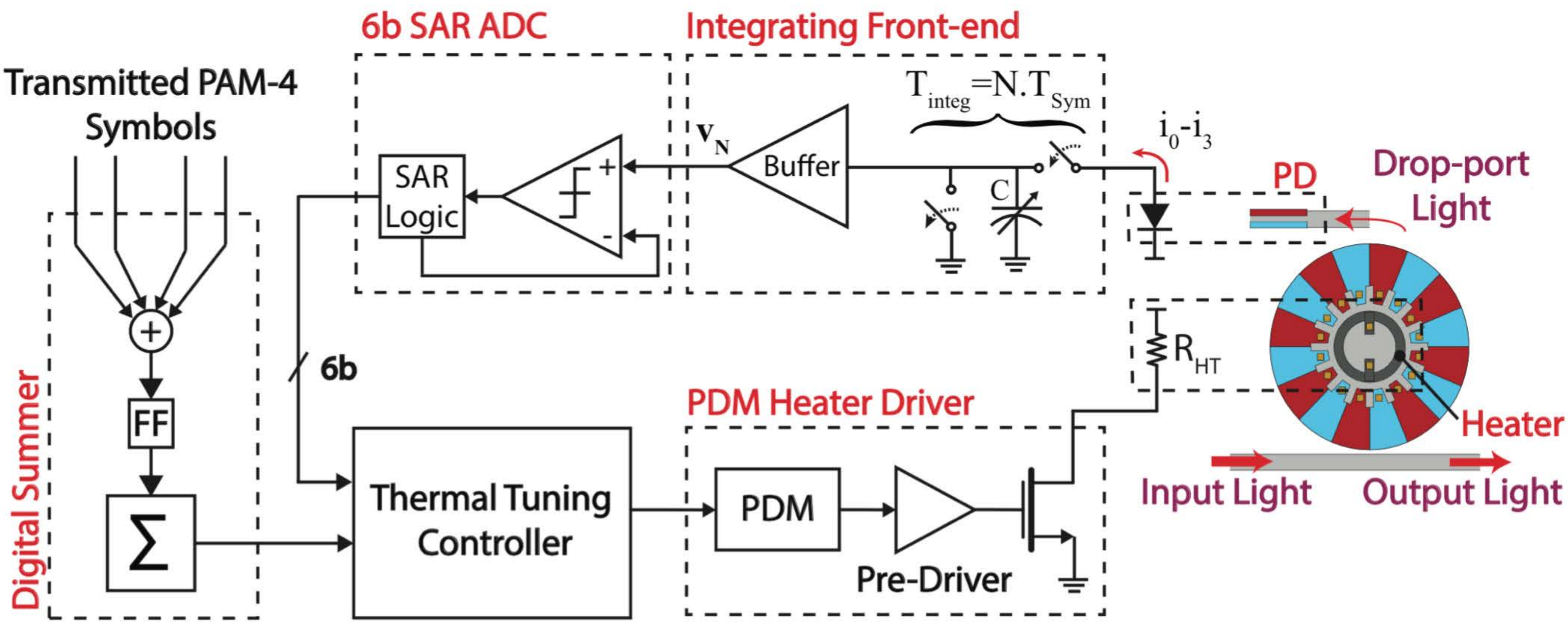
Ring-resonator based WDM link [C. Sun, JSSC 2016]

Thermal Sensitivity of Micro-rings

- Thermal Sensitivity of OMA $_{TX}$
    - Temperature variation sources: Circuits, Optical power inside the ring, …
- 10GHz/K shift for silicon microrings
- Main challenge on using this type of modulators commercially



Thermal Tuning



- Embedded resistive heater inside the ring
- Sense optical power & Adjust heater strength
- Finds and tracks the optimized ring resonance

[Moazeni *et al.*, JSSC 17]

Summary

- Optical interconnects are the backbone of internet & wireless networks and supercomputers

- Need for higher energy-efficiency & high-bandwidth density in photonic transceivers
  - Energy-efficient and compact photonic devices
  - Laser sources with higher wall-plug efficiency & multi-wavelength
  - Closer integration with advanced electronics

- Necessity of co-designing and co-optimization of electronic-photonic systems