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

- High data rate $\rightarrow$ High channel loss $\rightarrow$ 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!

**Power Consumption vs. Channel Loss**
- 5m 28Gb/s
- Voids optics can fill!

**Electrical Link Data-rates Trend**
- [Tech trends, ISSCC 2016]
# Data Center Interconnects

<table>
<thead>
<tr>
<th>Type</th>
<th>Range</th>
<th>Medium</th>
<th>Transmission Type</th>
</tr>
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<tbody>
<tr>
<td><strong>Long-span Inter-building</strong></td>
<td>40G → 100G → <strong>200G/400G</strong></td>
<td>Single-mode Fiber</td>
<td>Optical</td>
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<td></td>
<td>2km/metro</td>
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<tr>
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<tr>
<td></td>
<td>20m-2km</td>
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<tr>
<td></td>
<td>1-20 m</td>
<td>Multi-mode Fiber</td>
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<tr>
<td><strong>Intra-rack</strong></td>
<td>10G → <strong>56G</strong> → 100G/200G</td>
<td>Copper Channels</td>
<td>Electrical</td>
</tr>
<tr>
<td></td>
<td>0.5-3 m</td>
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Emerging Needs for Photonics

- 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) vs. 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

- 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**

- **Transmitter (Tx)**
  - Digital In
  - Electrical Driver
  - Laser

- **Optical Fiber**

- **Receiver (Rx)**
  - Optical Fiber
  - Electrical Rx
  - PD

**Externally Modulated Laser**

- **Electrical Driver**

- Optical Modulator

- **Optical Fiber**

- **Electrical Rx**
Eye-diagram & 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, ...

**Rx Bathtub curve for BER**

**Tx eye-diagram (NRZ Modulation)**

- Sampling phase
- $U_{\text{center}}$
- $\varphi = 0$, $\varphi = \pi$, $\varphi = 2\pi$
- 0 UI, $Q\sigma$, 1 UI
- $\sigma_0$, $\sigma_1$, $\mu_0$, $\mu_1$, $0.5 \times \text{DTD}$

**BER$_{\text{Left}}$**, **BER$_{\text{Right}}$**, **target BER**
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)
Optical Modulators

Electro-absorption based

Mach-Zehnder Modulator

Resonant Modulator

\[ I_{out} = I_{in} \times e^{-\Delta \alpha \cdot L} \]

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

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

\[ a = \text{round trip loss} \]
\[ \phi = \text{round trip phase shift} \]
Phase Shifters in Silicon

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

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

\[
\Delta n = \Delta n_e + \Delta n_h
\]

\[
= -8.8 \times 10^{-22} \Delta N_e - 8.5 \times 10^{-18} (\Delta N_h)^{0.8}
\]

\[
\Delta \alpha = \Delta \alpha_e + \Delta \alpha_h
\]

\[
= 8.5 \times 10^{-18} \Delta N_e + 6.0 \times 10^{-18} \Delta N_h
\]
Photodiodes (PD)

- 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

- 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

- Laser power: 160 mW
- 5% wall-plug efficiency
- 6.4 pJ/bit

Optical Power

- 9 dBm (8mW)
- 5 dBm
- 1 dBm
- -5 dBm
- -3 dBm
- -7 dBm
- -9 dBm
- -13 dBm

TX IN
Mod
TX OUT
chip1

RX IN
PD
chip2

Fiber

100 uA

-75 uA
RX sensitivity
25 Gb/s

Laser power: 160 mW

- 6.4 pJ/bit
- 5% wall-plug efficiency

Bit 1
- 100 uA
- 5 dBm

Bit 0
- 25 uA
- 9 dBm (8mW)

- 6.4 pJ/bit
- 5% wall-plug efficiency

Bit 1
- 100 uA
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Bit 0
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- 6.4 pJ/bit
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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

Grating Couplers
- Couple light from off-chip to on-chip
- 1dB/coupler loss
Energy-efficiency of Photonic Links

- **Commercial Silicon-Photonic**
  - Optical Link: 11pJ/b
  - Electrical Link: 15pJ/b
  - Transmission: 30pJ/b

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

Equation:

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

[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

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

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

[S. Lin, JLT17]
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

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

Hybrid / 3D

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

[IBM, OFC 16] [Luxtera, Hot Chips 09] [Roshan-Zamir, OI 16] [Luxtera, IEDM 17]
Foundry Movement in Photonics

Silicon-Photonics emerged as a viable solution

Major foundries now have Silicon-Photonic processes
Hybrid/3D Integrations

- 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

- $f_T$: Transistors' current gain unity frequency
- $f_T$ affects speed, energy-efficiency, sensitivity, ...
- Advanced transistors sensitivity to process change
Micro-ring Modulator (MRM)

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

- Modulation Scheme:
  1. Deplete/Inject carriers using PN junctions
  2. $\Delta$free carriers $\rightarrow$ $\Delta$index of refraction [Carrier-Plasma Effect]
  3. On-Off Keying (OOK) modulation
  
  * OMA: Optical Modulation Amplitude

[Courtesy of C. Sun]

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

Ring-resonator based WDM link [C. Sun, JSSC 2016]
Thermal Sensitivity of Micro-rings

- Thermal Sensitivity of OMA\textsubscript{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