Lecture 21: Optical I/O
Announcements

• Exam 2 is on Friday April 29
  • Comprehensive, but will focus on lectures 11 and later
  • 60 minutes
  • 1 standard 8.5x11 note sheet (front & back)
  • Bring your calculator
  • Lab solutions and last years exam posted on website

• No class next Monday or Tuesday
• Final Project Report Due Tuesday by 5PM
  • Email me a soft copy of your report
• Project Presentations Tuesday May 10, 8-10AM
  • Email me your presentation by 7AM
Agenda

• Electrical Channel Issues
• Optical Channel
• Optical Transmitter Technology
• Optical Receiver Technology
• Optical Integration Approaches
High-Speed Electrical Link System
Channel Performance Impact

Channel Responses

10Gb/s Pulse Responses

10Gb/s Eye - Desktop Channel

10Gb/s Eye - Refined BP Channel

10Gb/s Eye - Legacy BP Channel
Link with Equalization

 Serializer

 $D_{Tx[N:0]}$  

 TX FIR Equalization

 Channel

 RX Clk Recovery (CDR/Fwd Clk)

 RX CTLE + DFE Equalization

 Deserializer

 $D_{Rx[N:0]}$
Channel Performance Impact

Channel Responses

10Gb/s Equalized Pulse Responses

10Gb/s Eye - Desktop Channel w/ Eq

10Gb/s Eye - Refined BP Channel w/ Eq

10Gb/s Eye - Legacy BP Channel w/ Eq
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 \( \sim 0.25 \text{dB/km} \) at 1550nm
  - RF coaxial cable loss \( \sim 100 \text{dB/km} \) at 10GHz
- Frequency dependent loss is very small
  - \(<0.5 \text{dB/km} \) over a bandwidth >10THz
- Bandwidth may be limited by dispersion (pulse-spreading)
  - Important to limit laser linewidth for long distances (>1km)
Free-Space Optical Links

• 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 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 Cross-Section**

- Light output
- n-contact
- p-contact
- Top mirror
- Bottom mirror
- Oxide layer
- Gain region

**VCSEL L-I-V Curves**

- $I_{TH} = 700 \mu A$
- $\eta = 0.37 \text{mW/mA}$

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

Slope Efficiency: $\eta = \frac{\Delta P}{\Delta I} \left( \frac{\text{W}}{\text{A}} \right)$
VCSEL Bandwidth vs Reliability

10Gb/s VCSEL Frequency Response [1]

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

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

- Steep trade-off between bandwidth and reliability

\[ MTTF \propto \frac{1}{BW^4} \]

VCSEL Drivers

- 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)

• 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

QWAFEM Modulator*


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

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 with width <1µm (pitch ~4µm).
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

Mach-Zehnder Modulator (MZM)

- 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]

Light

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<tr>
<th>p</th>
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- Normally incident light absorbed in intrinsic region and generates carriers
- Trade-off between capacitance and transit-time
- Typical capacitance between 100-300fF

**Responsivity:**

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

**Quantum Efficiency:**

\[
\eta_{pd} = 1 - e^{-\alpha W}
\]

**Transit-Time Limited Bandwidth:**

\[
f_{3dBPD} = \frac{2.4}{2\pi \tau_r} = \frac{0.45 v_{sat}}{W}
\]
Integrated Ge MSM Photodetector

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

Very low capacitance: <1 fF
Active area: < 2 um²

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] Laser Diode Array

[Schow] CMOS IC

[Mohammed] Optical Connector

Wirebonding

Flip-Chip Bonding

Short In-Package Traces
Integrated CMOS Photonics

SOI CMOS Process

Bulk CMOS Process

“Optics On Top”

Optical Layer

[Analui]

[Young]

[Batten]
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!