Lecture 15: Optical I/O
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

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
Channel Performance Impact

Channel Responses

![Channel Responses Graph]

10Gb/s Equalized Pulse Responses

![10Gb/s Equalized Pulse Responses Graph]

10Gb/s Eye - Desktop Channel w/Eq

![10Gb/s Eye Desktop Channel Graph]

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

![10Gb/s Eye Refined BP Channel Graph]

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

![10Gb/s Eye Legacy BP Channel Graph]
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

- WDM allows for multiple high-bandwidth (10+ Gb/s) signals to be packed onto one optical channel

[Young JSSC 2010]
Optical Interconnects

- Electrical Channel Issues
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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)
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

[Gruber]
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]
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Optical Modulation Techniques

- Due to its 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 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 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**

**VCSEL L-I-V Curves**

$$I_{TH} = 700 \mu A$$

$$\eta = 0.37 \text{ mW/mA}$$

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

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

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

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

- Steep trade-off between bandwidth and reliability

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

VCSEL Drivers

Current-Mode VCSEL Driver

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

VCSEL Driver w/ 4-tap FIR Equalization

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.


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 < 20\(\mu\)m) 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)
Ring-Resonator-Based Silicon Photonics Transceiver

- 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

[Li ISSCC 2013]
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

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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

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

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<tr>
<th>Light</th>
<th>W</th>
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<tr>
<td>p InP</td>
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<td>i InGaAs</td>
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<td>n InP</td>
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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:

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

Quantum Efficiency:

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

Transit-Time Limited Bandwidth:

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

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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

One Driver

Wirebonding

[Schow] Optomodule

CMOS IC

Transceiver Optochip

Optical Connector

Optical Waveguide

VCSEL

CMOS Chip

PD

Output
Optical Connector

Package Substrate and Electrical IO

Board

Flip-Chip Bonding

[Mohammed] Photodiodes

Waveguides

CMOS

Tx Rx

Decoupling Capacitors

Optical Connector

Short In-Package Traces
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!