Announcements

• Project preliminary report due today

• Exam 2 is on Thursday April 25
  • Comprehensive, but will focus on lectures 7-14
  • 85 minutes
  • 1 standard 8.5x11 note sheet (front & back)
  • Bring your calculator

• Final project report due April 30

• Project presentations May 7 (1PM-3PM)
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  \( D_{TX}[N:0] \)  \( \rightarrow \)  \( \text{TX FIR Equalization} \)  \( \rightarrow \)  Channel  \( \rightarrow \)  \( \text{RX CTLE + DFE Equalization} \)  \( \rightarrow \)  deserializer  \( D_{RX}[N:0] \)

- TX Clk Generation (PLL)
- RX Clk Recovery (CDR/Fwd Clk)
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
• 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 J SSC 2010]
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• 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)

Optical Fiber Cross-Section

Single-Mode Fiber Loss & Dispersion

[Sackinger]
Inter-Chip Waveguide Examples

12-Channel Ribbon Fiber

[Reflex Photonics]
12 channels at a 250\(\mu\)m pitch
10Gb/s mod. \(\rightarrow\) 40Gb/s/mm

Optical Polymer Waveguide in PCB

[Immonen 2009]
<100\(\mu\)m channel pitch possible
10Gb/s mod. \(\rightarrow\) 100+Gb/s/mm

• Typical differential electrical strip lines are at \(~500\mu\)m pitch
Free-Space Optical Links

• Free-space (air or glass) interconnect systems have also been proposed

• Optical imaging system routes light chip-to-chip
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
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 J SSC 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 ($P_1/P_0$)

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

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

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

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

- Steep trade-off between bandwidth and reliability

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

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

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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

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

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
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

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

[Analui]
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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] [Light]

\[
p \quad \text{InP} \\
i \quad \text{InGaAs} \\
n \quad \text{InP}
\]

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

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

Transit-Time Limited Bandwidth:
\[
f_{3dBPD} = \frac{2.4}{2\pi \tau_{tr}} = \frac{0.45v_{sat}}{W}
\]

- 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

- 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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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

Wirebonding

Flip-Chip Bonding

Short In-Package Traces
Integrated CMOS Photonics

SOI CMOS Process [Analui]

Bulk CMOS Process

Optical Layer

“Optics On Top”

[Young]

[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!