ECEN689: Special Topics in High-Speed Links Circuits and Systems
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Lecture 33: Optical I/O

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Announcements

- Final Project Report Due Tomorrow by 5PM

- Project Presentations next Monday May 10, 8-10AM
Agenda

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

Serializing

TX Clk Generation (PLL)

TX FIR Equalization

Channel

RX Clk Recovery (CDR/Fwd Clk)

RX CTLE + DFE Equalization

Deserializer

$D_{Tx}[N:0]$

$D_{Rx}[N:0]$
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 \(~0.25\text{dB/km at 1550nm}\)
  - RF coaxial cable loss \(~100\text{dB/km at 10GHz}\)

- 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

For TIR: \( n_1 > n_2 \)

Single-Mode Fiber Loss & Dispersion

[Sackinger]
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 Cross-Section

- VCSEL emits light perpendicular from top (or bottom) surface
- Important to always operate VCSEL above threshold current, $I_{\text{TH}}$, to prevent “turn-on delay” which results in ISI
- Operate at finite extinction ratio $(P_1/P_0)$

![VCSEL Cross-Section Diagram]

VCSEL L-I-V Curves

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

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

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

$I_{\text{TH}} = 700 \mu\text{A}$
VCSEL Bandwidth vs Reliability

10Gb/s VCSEL Frequency Response [1]

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

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

- Steep trade-off between bandwidth and reliability

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

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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

QWAFEM Modulator*

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.

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

*S. Palermo* and *M. Horowitz*, “High-Speed Transmitters in 90nm CMOS for High-Density Optical Interconnects,” *ESSCIRC*, 2006.
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

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

- Normally incident light absorbed in intrinsic region and generates carriers
- Trade-off between capacitance and transit-time
- Typical capacitance between 100-300fF

[Sackinger]

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Responsivity:

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

Quantum Efficiency:

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

Transit-Time Limited Bandwidth:

\[ f_{3dBPD} = \frac{2.4}{2\pi \tau_r} = \frac{0.45 V_{\text{sat}}}{W} \]
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

- **Wirebonding**
- **Flip-Chip Bonding**
- **Short In-Package Traces**
Integrated CMOS Photonics

**SOI CMOS Process**

- Copper
- Poly
- Inter-Layer Dielectric (ILD)
- Field oxide
- "Active" Si
- "Handin" Si
- SOI transistor
- Waveguide
- SOI transistor

**Bulk CMOS Process**

- Polysilicon waveguide
- Etch hole
- Air gap

**Optical Layer**

- Detector
- Waveguide
- Modulator

**“Optics On Top”**

*[Analui]*

*[Batten]*

*[Young]*
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!