ECE 492-060/592-117
Silicon Photonic Design: Devices & Systems

Instructor(s): Stanley Cheung, scheung3@ncsu.edu

Objective or Description: This course focuses on applying advanced electromagnetic principles and semiconductor theory to design silicon photonic integrated circuits. Key principles such as matrix optics, waveguide theory, coupled mode theory, and P-I-N junctions will be used to design practical silicon photonic devices which are relevant in today's foundries. Topics include passive wavelength filters, active switches, high-speed optical modulators, and photodetectors for optical communication and computing systems. Special emphasis is placed on the interaction between guided EM waves and electrical charges in P-I-N junctions, providing a foundation for understanding and designing modern photonic devices (e.g., modulators, switches, and photodetectors) based on carrier injection and depletion in silicon/germanium integrated optics. The course also covers fabrication techniques and challenges associated with CMOS integration. Additionally, system-level analyses of short-reach and long-haul optical links will be explored, highlighting the design considerations for optical transmitter and receiver subsystems as well as individual devices. At the end of the course, students will be able to create a layout of a Si photonic PIC ready for tape-out at a particular foundry.

Prerequisites: ECE 302, ECE 303, MATLAB

Textbook: Silicon Photonics Design by Lukas Chrostowski (**ISBN-10:** 1107085454)
Photonics: Optical Electronics in Modern Communications by Amnon Yariv (**ISBN-10:**0195179463)

Topics:

1. **Introduction and review**: Optical communications: short-reach, long-haul, and data centers communications. Economic drivers towards photonic integration. Interaction of optical waves with dielectric and metal interfaces. Boundary conditions, total internal reflection. Review of silicon PN-and PIN-junctions. Junction diode static and transient characteristics.
2. **Fundamentals of Si photonics**: Symmetric dielectric waveguides. Asymmetric dielectric waveguides. Rectangular waveguides. Computational methods for integrated photonics. Effective index methods. Propagation matrix, finite difference time domain, eigenmode expansion. Design and fabrication of silicon waveguide structures. Waveguide loss, scattering, absorption, radiation. Adiabatic mode converters. Dispersion in optical waveguides, group delay, dispersion engineering
3. **Passive devices**: Coupling to waveguide: edge, grating, evanescent coupling, spot-size converters. Packaging solutions and economic/functional/power constraints. Coupled mode theory. Coupled optical waveguides. Power splitters. Mach-Zehnder interferometer. Cascaded MZI optical filters. Star couplers. Wavelength division multiplexing. Optical ring resonators. Add-drop multiplexers. Waveguide Bragg gratings. Polarization dependence and management. Waveguide polarization splitters and rotators. Optical isolation. Wavelength multiplexers figures of merit.
4. **Active devices**: Electro-optical effects in silicon. Thermal phase shifter, thermo-optic switch. Carrier-induced electro-optical effects. Carrier-Injection phase shifter. PN-junction carrier distribution, optical phase response, small signal response. Forward biased PIN junction variable optical attenuator. Micro-ring modulators and switches, small-signal response, ring modulator design. Carrier depletion phase shifter. PN-junction carrier distribution, optical phase response, small signal response. Traveling wave design of reverse-biased electro-optic modulator. Modulators for advanced modulation formats. Transmitter figures of merit. Germanium photodetectors. Fabrication approaches. III-V integration with silicon photonics. Integrated photodetectors, lasers and amplifiers. Receiver figures of merit.

5. **Optical communication systems**: Introduction to photonic systems for short-reach and long-haul optical communications. Modulation formats, receiver and transmitter characteristics, optical link budget, BER and penalties. Introduction to data center optical networks. Optical switching. Optical switches.
6. **Emerging systems**: Si photonics in quantum computing, neuromorphic computing, and biological sensing. Comparison of technological advantages and business models. State of silicon photonics industry. Skills and competencies.

Grading:

Homework and participation: 30%
Midterm Exam: 20%
Final Exam: 10%
Final Project: 40%

Cross-listing in other departments:

Integrated silicon photonic circuits have become a critical technology for next generation long-haul communication links, data-center interconnectivity for AI, and emerging applications such as quantum computing, optical accelerators, and biological/chemical sensing. This course will teach students how to design photonic circuits for these cutting edge applications. In the end, they will be able to layout a complete circuit ready for tape-out at a major foundry.