ECE442: Silicon Photonics   **Semester:** Fall 2021

CRN: 65456   **Credit:** 3 to 4 hours   **Prerequisite:** ECE350

Catalog description: Electromagnetic waves, silicon photonics, optical waveguides, waveguide couplers, waveguide filters, photonic electro-optical devices, silicon photonic modulators, germanium photodetectors, optical communications systems.
Total contact hours: 4.5 hours/week

Course Topics:	Hours (approx.)
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.	4
2. **Fundamentals of Si photonics**: Symmetric dielectric waveguides. Asymmetric dielectric waveguides. Rectangular waveguides. Computational methods for integrated photonics. Marcatilli's and 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.	8
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.	8
4. **Transmitter 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.	10
5. **Receiver active devices**: Germanium photodetectors. Fabrication approaches. III-V integration with silicon photonics. Integrated photodetectors, lasers and amplifiers. Receiver figures of merit.	4
6. **Photonic 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.	3
7. **Emerging applications** of 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.	5
Exams	3

TOTAL =   45

Basis for grade:

Homework and participation	20%
Exam I	25%
Exam II	25%
Final Exam	30%
Total	100%

Additional credit: Up to 4 graduate hours will be given on the basis of successfully completing independent project on analysis, design and testing of the silicon photonic circuits via participation in "Silicon Photonics Design, Fabrication and Data Analysis" web-based course. Designs should be completed by the tapeout date in the mid-February. Corresponding photonic devices and circuits will be fabricated at the University of British Columbia and then automatically tested. Results of the optical measurements will be available for students by mid-March. This will give enough time to analyze the results and write a comprehensive report covering device operation principles, literature search, design approaches chosen, and analysis of the experimental results.

OFFICIAL DESCRIPTION

Silicon photonics is a rapidly growing industry as well as an active area of research. This course will focus on practical applications of advanced EM concepts to photonics integrated circuits. It combines the rigorous derivation of major physical concepts like matrix optics, waveguiding, coupled mode theory, pin junctions, etc. with the applications of these knowledge towards the design of practical silicon photonic devices like passive wavelength filters, active switches, modulators, and photodetectors for optical communications systems. The emphasis will be given to interaction of guided EM waves with electrical charges in pin junction that would allow to understand the operation and design principles of a new class of photonic devices (modulators, switches, photodetectors, etc.) based on carrier-injection/depletion in silicon/germanium integrated optics. Fabrication approaches and CMOS integration challenges will be reviewed. System-level analysis of short-reach and long-haul optical links will be reviewed that will drive the design considerations for optical transmitter and receiver subsystems and individual devices.

SUBJECT AREA

Microelectronics and Photonics

DETAILED DESCRIPTION AND OUTLINE

1. Optical communications: short-reach, long-haul, and data centers communications. Economic drivers towards photonic integration.
2. Symmetric dielectric waveguides. Computational methods for integrated photonics. Propagation matrix, finite difference time domain, eigenmode expansion. Design of waveguide structures.
3. Coupling to waveguide: edge, grating, evanescent coupling, spot-size converters. Packaging solutions and economic/functional/power constraints.
4. Cascaded MZI optical filters. Star couplers. Wavelength division multiplexing. Filters figures of merit.
5. Electro-optical effects. Phase and amplitude modulators. Index modulation in silicon. Thermal phase shifter, thermo-optic switch.
6. Review of PN-and PIN-junctions. Junction diode static and transient characteristics. Carrier-induced electro-optical effects.
7. Micro-ring modulators and switches, small-signal response, ring modulator design. Traveling wave design of reverse-biased electro-optic modulator. Design tradeoffs.
8. Introduction to short-reach and long-haul optical communications. Modulation formats, receiver and transmitter characteristics, optical link budget, BER and penalties
9. III-V integration with silicon photonics. Integrated lasers and amplifiers. Transmitter figures of merit.
10. Introduction to data center optical networks. Optical switching. Optical switches.
11. State of silicon photonics industry. Skills and competencies.

COMPUTER USAGE

Students are encouraged to solve some of the homework problems using computers. Optional participation in the independent design project requires simulation of guided properties of various silicon photonics devices using industrial finite-difference time-domain and finite element simulation package.

TOPICAL PREREQUISITES

Electromagnetic wave propagation at an intermediate level

TEXTS

No single textbook covers all topics. The course will rely on recent news items, journal papers, lecture handouts, lecture notes/slides, and reading sections from several books including:
S.L.Chuang, Physics of Photonic Devices, second edition, Wiley, New York, 2009.
B. Saleh and M.C. Teich, Fundamentals of Photonics, 2nd ed., Wiley, 2007.
L. Coldren, S. Corzine, M.L. Mashanovitch , Diode Lasers and Photonic Integrated Circuits, Wiley 2nd Edition (2012)

COURSE GOALS

The goals of this course are to teach advanced concepts in electromagnetics and guided wave optics including guided electromagnetic waves, applications to as integrated waveguide-based optoelectronic devices including passive and active devices based on electro-optical effects.

INSTRUCTIONAL OBJECTIVES

A. By the time of Exam I (after 10 lectures, 80 minutes per lecture), the students should be able to do the following:

1. Formulate and calculate plane wave reflection coefficients from a planar boundary between two dielectric media. Understand the principle of total internal reflection and its consequences for reflected and transmitted waves.
2. Find the analytical expressions for the electromagnetic fields and guidance conditions in symmetric dielectric waveguides.
3. Calculate the propagation constant and effective index, optical confinement factor for a given guided optical mode in a dielectric waveguide. Find the cutoff conditions, cutoff frequency and general solutions for TE and TM modes in asymmetric dielectric waveguides.
4. Find the guidance condition and general solutions for the modes in rectangular dielectric waveguide using effective index method.
5. Apply coupled-mode theory to calculate power exchange in coupled optical waveguides.
6. Understand the principles of for wavelength division multiplexing (WDM) for optical communications.
7. Design and analyze waveguide-based Mach-Zehnder interferometer, cascaded MZI filters and star couplers.
8. Design and analyze optical ring resonators, optical couplers, and add-drop filters.
9. Understand principles of computational methods for integrated photonics including propagation matrix, finite difference time domain, eigenmode expansion methods.
10. Compute power loss of a guided mode due to scattering, absorption, and radiation.

B. By the time of Exam II (after 19 lectures, 80 minutes per lecture), the students should be able to do all of the items listed under A, plus the following:
11. Understand polarization dependence and management in optical waveguides. Apply this knowledge to design integrated polarization splitters and rotators.
12. Understand various electro-optical effects (free carrier induced, thermal, Franz-Keldysh, etc.) used for index modulation in silicon photonics. Understand the principles of operation of integrated phase and amplitude modulators.
13. Calculate the efficiency of thermal phase shifter, design thermo-optic switch.
14. Understand principles of operation of a carrier-Injection phase shifter.
15. Apply this knowledge to design forward biased PIN junction variable optical attenuators, micro-ring modulators and switches.
16. Understand principles of operation of a carrier-depletion phase shifter.
17. Apply this knowledge to design reverse-biased electro-optic modulators.
18. Understand the concepts of group velocity and dispersion (material, modal, waveguide) in waveguides.
19. Calculate dispersion and attenuation in optical waveguides.
20. Understand signal distortion in optical waveguides, group delay and its application to dispersion engineering.

C. By the time of Final Exam (after 27 lectures, 80 minutes per lecture), the students should be able to do all of the items listed under A and B, plus the following:

21. Understand principles and technologies used for short-reach and long-haul optical communications.
22. Understand system level design principles of optical communication systems including modulation formats, receiver and transmitter characteristics, optical link budget, bit error rates and link power penalties
23. Understand principles of operation of waveguide photodetectors. Calculate photodetector responsivity, quantum efficiency, receiver power penalty.
24. Understand various approaches for integration of lasers and amplifiers with integrated photonic circuits.
25. Understand physical origin of optical nonlinearities in optical waveguides. Apply this knowledge to design wavelength converters and frequency comb generators.
26. Emerging. Comparison of technological advantages and business models
27. Be versed on the major scientific discoveries and technical advances that led to today's state of the art in integrated photonics technology and its applications optical communications, quantum computing, neuromorphic computing, and biological sensing.
28. Be interested in and comfortable with applying the concepts and mathematical tools they learned in this course to advance their learning and understanding of optoelectronic devices and systems.