Opti 553: Nonlinear Photonics

Professor:
Professor Robert A. Norwood, College of Optical Sciences, Room 533, Lab 506
520-626-0936; rnorwood@optics.arizona.edu

Teaching Assistant:
Sifang Cui, scui@optics.arizona.edu

Lectures: Monday and Wednesday at 2:00 – 3:15 in Meinel 305; in-person

Office Hours: By appointment

Course Description: This course will start with a review of key concepts from 510R *Photonics* including the generalized constitutive relationship between polarization and electric field and the optical physics of waveguides. Key optical waveguide building blocks such as directional couplers, Y-splitters, and Mach-Zehnder interferometers will be discussed, as well as trends in integrated photonics, especially silicon photonics. Second-order nonlinear optical phenomena such as second harmonic generation, the Pockels effect, sum and difference frequency mixing, and optical parametric amplification will be introduced through the nonlinear optical susceptibility framework, and specific second NLO devices of significant technological impact such as integrated electro-optic modulators, quasiphasematched waveguide frequency doublers and terahertz generation devices will be discussed, analyzed and modeled; devices used for quantum communications will be introduced. Careful consideration of the NLO materials requirements and state-of-the-art materials choices will be integrated directly into the development of second-order nonlinear photonics. The course will then move on to similarly treat third order NLO, focusing on the nonlinear photonics of optical fiber, high index contrast optical waveguides, and nanophotonic systems; fundamental considerations regarding the development of third order nonlinear optical materials will be addressed. Advanced topics to be discussed will include stimulated Raman scattering, surface plasmon resonance phenomena, nonlinear optical effects in quantum confined structures, and the nonlinear optics of 2D materials, as well as other topics that arise in class discussion.

Course Objectives:

- Provide a thorough foundation in the optical physics of both second order and third order nonlinear optical phenomena, including an understanding of material requirements, approaches to solving Maxwell's equations in the presence of nonlinear polarization, and quantum mechanical descriptions of NLO phenomena.
- Provide students with an understanding of optical waveguide physics and integrated optical device building blocks sufficient to perform the design of nonlinear photonic devices.

- Comprehensively discuss several technologically significant nonlinear photonics devices/phenomena including quasiphasematched frequency doublers, parametric frequency converters, microresonators, stimulated Raman scattering and all-optical switches among other topics.
- Introduction to advanced concepts in nonlinear photonics including plasmonics, quantum confined structures, quantum photonics and graphene nonlinear optics.

Learning Outcomes:
Upon completion of this course, students will be able to

- Analyze both two-dimensional and three-dimensional optical waveguides and determine the number of waveguide modes, the effective index and confinement factor of a given mode, as well as describe the waveguide in terms of generalized waveguide parameters;
- Design passive integrated photonics building blocks such as directional couplers and Y-junctions;
- Derive the relevant nonlinear polarization for any second or third order nonlinear optical process in any specific material medium;
- Solve Maxwell's equations for waveguide geometries consistent with efficient nonlinear photonics processes relevant to commercial devices;
- Analyze short pulse propagation through an optical fiber including full consideration of self-phase modulation and Raman contributions to the nonlinear photonic response**;**
- Design quasiphasematched frequency conversion devices (bulk and waveguide), modal frequency conversion devices, and all-optical switches;
- Calculate the basic resonant frequencies and properties of multiple quantum wells, plasmonic structures, and additional nanophotonic building blocks.

Grading

- Homework assignments - 30%
- Midterm exam – 30%
- Final exam – 40%

The grade will be determined according to the cumulative percentage earned such that 90-100% = A, 80-89% = B, 70-79% = C, 60-69% = D, below 60% = E.

Required Text
Nonlinear Optics by Robert W. Boyd (3rd Edition). This text is freely available on-line at www.sciencedirect.com. We will also make use of *Nonlinear Fiber Optics* by G. P. Agrawal (Fifth Edition) also available at www.sciencedirect.com. Additional readings and notes will be provided from a variety of sources.

Course Outline

1. Brief Review of Electromagnetic Theory and Guided Waves

   a. Maxwell's equations
   b. Fresnel relations

c. Guided waves

2. **Step-Index Thin-film Waveguides**
    - **a.** Dispersion relation
    - **b.** Generalized parameters
    - **c.** Fields of step-index waveguides
    - **d.** Loss in thin-film waveguides
3. **Three-Dimensional Waveguides**
    - **a.** Rectangular waveguide modes
    - **b.** Marcatili method
    - **c.** Effective index method
4. **Optical Directional Couplers**
    - a. Coupled-mode description
    - b. Reverse $\Delta\beta$ couplers
5. **High Index Contrast Waveguides**
    - a. Materials consideration
    - b. Microring resonators
    - c. Slot waveguides
6. **Nonlinear Optical Susceptibility**
    - a. Introduction to nonlinear optics (NLO)
    - b. Formal definition of nonlinear susceptibility
    - c. General properties
    - d. Macroscopic and microscopic quantities
    - e. Units
7. **Second Order NLO - $\chi^{(2)}$**
    - a. $\chi^{(2)}$ wave equation
    - b. $\chi^{(2)}$ tensor and symmetry considerations
    - c. Second harmonic generation (SHG)
    - d. Phasematching and quasiphasematching (QPM)
    - e. Sum frequency generation (SFG)
    - f. Difference frequency generation (DFG)
    - g. Electro-optic (Pockels) effect
8. **$\chi^{(2)}$ Materials**
    - a. Perovskite crystals (lithium niobate, lithium tantalate, etc.)
    - b. Other crystals (quartz, BBO, aluminum nitride,….)
    - c. Poled polymers
9. **$\chi^{(2)}$ Devices**
    - a. QPM waveguide frequency doublers
    - b. Difference frequency generation – quantum entanglement
    - c. Integrated electro-optic devices
10. **Third Order NLO - $\chi^{(3)}$**
    - a. $\chi^{(3)}$ wave equation
    - b. $\chi^{(3)}$ tensor and symmetry considerations
    - c. Origin of $\chi^{(3)}$
    - d. Electronic $\chi^{(3)}$
    - e. Thermal $\chi^{(3)}$

f. Band filling and population dependent $\chi^{(3)}$
g. Intensity dependent refractive index – n_2

11. $\chi^{(3)}$ Effects

a. Third harmonic generation (THG)
b. Four-wave mixing (FWM)
c. Self-focusing (SF)
d. Self-phase modulation (SPM) and cross-phase modulation (XPM)
e. Optical Kerr effect (OKE)
f. Stimulated Raman scattering (SRS)
g. Stimulated Brillouin scattering (SBS)
h. Nonlinear absorption (NLA)

12. $\chi^{(3)}$ Materials

a. Glasses
b. Semiconductors
c. Organic/Polymeric
d. 2D Materials

13. Nonlinear Photonics in Single-mode Optical Fibers

a. Review of LP modes
b. Propagation of pulses in single-mode fibers
c. Nonlinear envelope equation
d. Self-phase modulation
e. Stimulated Raman scattering
f. Stimulated Brillouin scattering

14. Advanced Topics

a. Quantum confined structures
b. Plasmonics
c. Nonlinear photonics in 2D materials
d. Nonlinear photonics and quantum communications

Exams: There will be two exams in the course, a mid-term and a final exam. The final exam will be a take home exam that will be distributed on December 3th and due on December 8th (the last day of class). The mid-term exam will occur in mid-October and will be in-class.

Equipment and software requirements: For this class you will need daily access to the following hardware: laptop or web-enabled device; regular access to reliable internet signal; ability to download and run the following software: web browser of choice, Adobe Acrobat, Matlab, Office 365 software.

Classroom attendance:

- If you feel sick, or may have been in contact with someone who is infectious, stay home. Except for seeking medical care, avoid contact with others and do not travel.
- Notify your instructor(s) if you will be missing a course meeting or an assignment deadline.
- Non-attendance for any reason does **not** guarantee an automatic extension of due date or rescheduling of examinations/assessments.

    - Please communicate and coordinate any request directly with your instructor.
- If you must miss the equivalent of more than one week of class, you should contact the Dean of Students Office DOS-deanofstudents@email.arizona.edu to share documentation about the challenges you are facing.
- Voluntary, free, and convenient COVID-19 testing is available for students on Main Campus.
- COVID-19 vaccine is available for all students at Campus Health.
- Visit the UArizona COVID-19 page for regular updates.

Academic advising: If you have questions about your academic progress this semester, please reach out to your academic advisor (https://advising.arizona.edu/advisors/major). Contact the Advising Resource Center (https://advising.arizona.edu/) for all general advising questions and referral assistance. Call 520-626-8667 or email to advising@.arizona.edu

Life challenges: If you are experiencing unexpected barriers to your success in your courses, please note the Dean of Students Office is a central support resource for all students and may be helpful. The Dean of Students Office can be reached at (520) 621-2057 or DOS-deanofstudents@email.arizona.edu.

Physical and mental-health challenges: If you are facing physical or mental health challenges this semester, please note that Campus Health provides quality medical and mental health care. For medical appointments, call (520) 621-9202. For After Hours care, call (520) 570-7898. For the Counseling & Psych Services (CAPS) 24/7 hotline, call (520) 621-3334.

Academic Integrity (http://web.arizona.edu/~studpubs/policies/cacaint.htm)
According to the Arizona Code of Academic Integrity "Integrity is expected of every student in all academic work. The guiding principle of academic integrity is that a student's submitted work must be the student's own." Unless otherwise noted by the instructor, work for all assignments in this course must be conducted independently by each student. Co-authored work of any kind is unacceptable. Misappropriation of exams before or after they are given will be considered academics misconduct.

Misconduct of any kind will be prosecuted and may result in any or all of the following:

- Reduction of grade
- Failing grade
- Referral to the Dean of Students for consideration of additional penalty, i.e. notation on a student's transcript re. academic integrity violation, etc.

Accessibility and Accommodations
At the University of Arizona, we strive to make learning experiences as accessible as possible. If you anticipate or experience barriers based on disability or pregnancy,

please contact the Disability Resource Center (520-621-3268, https://drc.arizona.edu/) to establish reasonable accommodations.

The information contained in this syllabus, other than the grade policies, may be subject to change with reasonable advance notice, as deemed appropriate by the instructor.