EE 531: Nonlinear Optics

USC Viterbi School of Engineering
4 Units | Mon/Wed, 10:00-11:50am | Location: DMC 257 | Fall 2023

Instructor: Chia Wei (Wade) Hsu, cwhsu@usc.edu
Office Hour: Wed 8:50-9:50am | Location: PHE 610

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Office Hour: Thur 11am-1pm | Location: PHE 320

Course Webpage: https://blackboard.usc.edu

Final exam time: 8am on Monday December 11th

Course Description

While the interactions between light and matter are typically linear—twice the input yields twice the output—such linearity breaks down at high intensities. In the nonlinear regime, two light beams can effectively interact with each other (superposition no longer holds), as the optical properties of the material system depend on the presence of light fields. Nonlinear optics involves rich fundamental physics, advanced mathematics and numerical methods, and is used for numerous technologies such as the generation of new frequencies (eg, green laser pointers and supercontinuum light sources), creation of short laser pulses, electro-optic modulators, laser machining, laser surgery, nonlinear spectroscopies, fiber optical communication with solitons, and optical computing. Nonlinear optics is also an important tool for metrology, sensing, and quantum optics.

This course will introduce the principles of nonlinear optics, the most common nonlinear phenomena, and their applications. It will cover the following topics: Nonlinear susceptibilities and anharmonic oscillator. Symmetries of linear and nonlinear susceptibility tensors. Effective nonlinear coefficients. Harmonic, sum, and difference frequency generation. Phase matching and quasi phase matching. Kerr effect. Self-focusing. Spatial and temporal solitons. Nonlinear pulse propagation. Split-step Fourier method. Electrooptic (EO) effect. Phase conjugation. Maxwell–Bloch equations.

Learning Objectives

Upon successful completion of this course a student will be able to

- understand the origin of nonlinear susceptibilities and their properties
- model frequency generation processes
- analyze and solve nonlinear wave equations
- apply phase matching for nonlinear effects to build up coherently
- model spatial and temporal solitons
- apply electrooptic effect for modulations

Prerequisite: EE 572. If you have taken an electrodynamics course elsewhere at an upper-undergraduate level or above, you can waive this prerequisite; please contact the instructor with your 10-digit USC ID for the waiver. *You must already know Maxwell's equations for macroscopic media in differential form, Fourier transforms, and how to solve elementary ordinary differential equations.*

Main Course Textbooks

1) Robert W. Boyd, *Nonlinear Optics (4rd edition)*, Elsevier Academic Press (2020); ISBN 978-0-12-811002-7; available for download with USC account at https://www-sciencedirect-com.libproxy1.usc.edu/book/9780128110027/nonlinear-optics
   A partial errata: http://www.boydnlo.ca/wp-content/uploads/2019/02/Errata-Boyd-NLO.pdf
2) Govind Agrawal, *Nonlinear Fiber Optics (6th edition)*, Elsevier Academic Press (2019); ISBN 978-0-12-817042-7; available for download with USC account at https://www-sciencedirect-com.libproxy2.usc.edu/book/9780128170427/nonlinear-fiber-optics

Supplementary Materials

1) Y. R. Shen, The Principles of Nonlinear Optics, Wiley, NY (2002); ISBN 978-0-471-43080-3.
2) P. N. Butcher, *The Elements of Nonlinear Optics*, Cambridge University Press (1990); ISBN 9781139167994; available for download with USC account at https://www.cambridge.org/core/books/elements-of-nonlinear-optics/F6B3C66E6115CD3DE8F615DF16BBB47C
3) V. G. Dmitriev, G. G. Gurzadyan, D. N. Nikogosyan, *Handbook of Nonlinear Optical Crystals*, Springer (1999); ISBN 978-3-540-46793-9; available for download with USC account at https://link-springer-com.libproxy1.usc.edu/book/10.1007%2F978-3-540-46793-9
4) Fredrik Jonsson, *Lecture Notes on Nonlinear Optics* (2003); online material, available at http://jonsson.eu/research/lectures
5) NPTEL *Nonlinear Optics* Course (2015); online material, available at https://nptel.ac.in/courses/115101008/

Grading Breakdown

40% Problem sets
15% Midterm Exam
20% Project (10% write-up, 10% presentation)
25% Final Exam

Problem Sets Description & Policy

- There will be 7 problem sets (~weekly in the first 10 weeks).
- Will be posted on Blackboard.
- **Due in class at the class start time.**
- Solutions will be posted on Blackboard on the due date after the lecture.
- **Late submission is not accepted** since the solution will be posted by that time. Late or no submission results in a zero grade.
- Show your work. **Problem sets are graded based on the entirety of your solution, not just the final answer.**
- You are encouraged to discuss problems and solution strategies with your classmates, the TA, and/or the instructor. However, each person must solve all problems independently.
- You may not copy the problem solutions from anybody else or from any existing solution. If found doing so, you'll receive a zero grade and be reported (see https://viterbischool.usc.edu/academic-integrity).
- For computer-based assignments, no code can be shared or copied from the internet. The only exception is code provided to the entire class by the instructor or TA.
- **Questions on clarification of the homework problems, if any, must be communicated to the instructor at least 24 hours before the due time**.

Final Project Description & Policy

- There will be one final project. The student selects a special topic in nonlinear optics (can be based on research interests and/or recent publications), writes a **short overview** on that topic, and presents it in class during the last week of class. The goal is for you and for the other students to learn about other topics in nonlinear optics that we do not cover in our lectures. Discuss your selection of topic with the instructor.
- Project timeline:
    - Week 11, Mon 10/30: Project description given.
    - Week 12, Mon 11/06: Project topic due.
    - **Week 15, Mon 11/27: Project write-up due by end of day.**
    - **Week 15, Mon 11/27 & Wed 11/29: In-class presentations.**
- The write-up and the presentation each count toward 10% of the course grade. As such, the expected amount of work (write-up + presentation) is roughly that of 4 problem sets, and the student has 4 weeks (week 11 through week 14) to work on the final project.
- **The write-up should be 2-4 pages**, in a **single-spaced double-column** style like a journal paper.
- **Each presentation will be 10 minutes max + 2 minutes for questions**.
- The final project will be graded based on (1) whether the topic and the amount of work is appropriate, and (2) the clarity and effectiveness of the presentation and write-up. Novelty/originality is not required.
- **If you cannot make the scheduled time of the final project presentation, you must notify and discuss with the instructor before the last day to drop a class without a W on the transcript.**

Exam Description & Policy

- **Midterm Exam: in class on Mon 10/16 (week 9)**
- **Final Exam: 8am Monday Dec 11th (final week)**
- The exams are **closed book**, but you may bring **up to two pages (can be double-sided, so up to four sides) of note of your own**.
- The scope of the midterm includes all materials up to the midterm. The scope of the final includes all materials over the semester.
- **If you cannot make the scheduled time of the midterm or final, you must notify and discuss with the instructor before the last day to drop a class without a W on the transcript.**
- For requests for accommodations due to disabilities, provide letter from the Office of Disability Services and Programs (DSP) to the instructor.

Course Schedule

Date	Topic	Reading
Week 1 8/21, 8/23	Course info and overview. Linear vs nonlinear optics. Superposition principle. Coupling/decoupling of frequencies. Drude–Lorentz model. HW 1 assigned.	Boyd 2.1, 1.1
Week 2 8/28, 8/30	Anharmonic oscillator. Overview of nonlinear processes. Formal definition of the susceptibility tensors. HW 1 due on 8/30. HW 2 assigned.	Boyd 1.4.1, 1.2, 1.3
Week 3 9/6	*No class on Mon 9/4 (Labor Day).* Intrinsic and partial permutation symmetry. Inversion symmetry. Crystal class and spatial symmetries.	Boyd 1.5
Week 4 9/11, 9/13	Spatial symmetries of $\chi^{(1)}$ and $\chi^{(2)}$. Contracted notation. Effective nonlinear coefficients. Kleinman's symmetry. HW 2 due on 9/13.	Boyd 1.5 Butcher 5.3 Dmitriev 2.10
Week 5 9/18, 9/20	Maxwell's equations with nonlinear polarizability. Sum frequency generation (SFG) without pump depletion. Phase matching. Ordinary & extraordinary indices. HW 3 assigned.	Boyd 2.1, 2.2, Butcher 7.1
Week 6 9/25, 9/27	Type I and Type II phase matching. Quasi-phase matching. Coupled nonlinear wave equations. HW 3 due on 9/25. HW 4 assigned.	Boyd 2.3, 2.4
Week 7 10/2, 10/4	Manley-Rowe relations. SFG with partial pump depletion. Tensor nature of $\chi^{(3)}$. HW 4 due on 10/2. HW 5 assigned.	Boyd 2.5, 2.6, 4.2
Week 8 10/9, 10/11	Intensity dependent refractive index and its polarization dependence. $\chi^{(3)}$ from bound electrons, thermal effects, and in semiconductors. Review. HW 5 due on 10/9.	Boyd 4.3, 4.5, 4.6
Week 9 10/16, 10/18	Midterm Exam in class on Mon 10/16 Self-focusing. Gaussian beam and diffraction. HW 6 assigned.	Boyd 7.1, 2.10
Week 10 10/23, 10/25	Nonlinear Schrodinger equation (NLSE). Spatial soliton: qualitative picture, solution in 1+1D and 1+2D, and stability. Numerical solution of NLSE with split-step Fourier method. Higher-order solitons. Soliton perturbations & interactions. HW 6 due on 10/23. HW 7 assigned.	Agrawal 2.4, 5.2.2
Week 11 10/30, 11/1	Project description. Pulse propagation. Group velocity dispersion. Instantaneous frequency. Waveguide/fiber modes. Nonlinear Maxwell's equations for pulse envelopes. HW 7 due on 10/30.	Boyd 7.5 Agrawal 2.2, 2.3
Week 12 11/6, 11/8	Equivalence between spatial and temporal solitons. Electrooptic (EO) effect: Pockels effect and Kerr EO effect. EO phase and intensity modulators. Project topic due on 11/6.	Agrawal 3.1 Boyd 11.1, 11.3

Week 13 11/13, 11/15	Phase conjugation. Nonlinearity of gain media. Maxwell–Bloch equations.	Boyd 7.2, 6.1-6.4
Week 14 11/20	Review *No class on Wed 11/22 (Thanksgiving)*	
Week 15 11/27, 11/29	Project write-up due on Mon 11/27 by end of day Project presentations in class	
Final Week	Final Exam: 8am Monday Dec 11th	

Statement on Academic Conduct and Support Systems

Academic Conduct:

Plagiarism – presenting someone else's ideas as your own, either verbatim or recast in your own words – is a serious academic offense with serious consequences. Please familiarize yourself with the discussion of plagiarism in SCampus in Part B, Section 11, "Behavior Violating University Standards" policy.usc.edu/scampus-part-b. Other forms of academic dishonesty are equally unacceptable. See additional information in SCampus and university policies on scientific misconduct, policy.usc.edu/scientific-misconduct.

Support Systems:

Counseling and Mental Health - (213) 740-9355 – 24/7 on call
studenthealth.usc.edu/counseling
Free and confidential mental health treatment for students, including short-term psychotherapy, group counseling, stress fitness workshops, and crisis intervention.

National Suicide Prevention Lifeline - 1 (800) 273-8255 – 24/7 on call
suicidepreventionlifeline.org
Free and confidential emotional support to people in suicidal crisis or emotional distress 24 hours a day, 7 days a week.

Relationship and Sexual Violence Prevention and Services (RSVP) - (213) 740-9355(WELL), press "0" after hours – 24/7 on call
studenthealth.usc.edu/sexual-assault
Free and confidential therapy services, workshops, and training for situations related to gender-based harm.

Office of Equity and Diversity (OED)- (213) 740-5086 | Title IX – (213) 821-8298
equity.usc.edu, titleix.usc.edu
Information about how to get help or help someone affected by harassment or discrimination, rights of protected classes, reporting options, and additional resources for students, faculty, staff, visitors, and applicants. The university prohibits discrimination or harassment based on the following *protected characteristics*: race, color, national origin, ancestry, religion, sex, gender, gender identity, gender expression, sexual orientation, age, physical disability, medical condition, mental disability, marital status, pregnancy, veteran status, genetic information, and any other characteristic which may be specified in applicable laws and governmental regulations. The university also prohibits sexual assault, non-consensual sexual contact, sexual misconduct, intimate partner violence, stalking, malicious dissuasion, retaliation, and violation of interim measures.

Reporting Incidents of Bias or Harassment - (213) 740-5086 or (213) 821-8298
usc-advocate.symplicity.com/care_report

Avenue to report incidents of bias, hate crimes, and microaggressions to the Office of Equity and Diversity |Title IX for appropriate investigation, supportive measures, and response.

The Office of Disability Services and Programs - (213) 740-0776
dsp.usc.edu
Support and accommodations for students with disabilities. Services include assistance in providing readers/notetakers/interpreters, special accommodations for test taking needs, assistance with architectural barriers, assistive technology, and support for individual needs.

USC Support and Advocacy - (213) 821-4710
uscsa.usc.edu
Assists students and families in resolving complex personal, financial, and academic issues adversely affecting their success as a student.

Diversity at USC - (213) 740-2101
diversity.usc.edu
Information on events, programs and training, the Provost's Diversity and Inclusion Council, Diversity Liaisons for each academic school, chronology, participation, and various resources for students.

USC Emergency - UPC: (213) 740-4321, HSC: (323) 442-1000 – 24/7 on call
dps.usc.edu, emergency.usc.edu
Emergency assistance and avenue to report a crime. Latest updates regarding safety, including ways in which instruction will be continued if an officially declared emergency makes travel to campus infeasible.

USC Department of Public Safety - UPC: (213) 740-6000, HSC: (323) 442-120 – 24/7 on call
dps.usc.edu
Non-emergency assistance or information.