EE 531: Nonlinear Optics

USC Viterbi School of Engineering
4 Units | Wed/Fri, 3:00-4:50pm | Location: Online | Spring 2021

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Office Hours: Mon, 3:00-4:55pm | Location: Online

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

Final exam time: 8am Monday 5/10 – 8am Tuesday 5/11

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 depends 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. Tensors. Spatial and permutation symmetries of linear and nonlinear susceptibilities. Effective nonlinear coefficients. Harmonic, sum, and difference frequency generation. Phase-matching and quasi-phase matching. Kerr effect. Self-focusing. Spatial solitons. Filamentation. Optical phase conjugation. Nonlinear pulse propagation. Temporal solitons. Modulation instability. Stimulated Raman scattering (SRS) and coherent anti-Stokes Raman spectroscopy (CARS). Electrostriction and stimulated Brillouin scattering (SBS). Electrooptic effect.

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;
- understand stimulated Raman and Brillouin scattering;
- apply electrooptic effect for modulations

Prerequisite: EE 470. If you have taken an equivalent course elsewhere (*i.e.*, electrodynamics at an upper-undergraduate level or above), please contact the instructor with your USC ID for prerequisite waiver. Student must be familiar with the macroscopic Maxwell's equations in differential form.

Wellness days:
There are university wellness days for the Spring 2021 semester. Therefore, we will not have class on the following days: Friday 3/12, Wednesday 4/7, Friday 4/30.

Main Course Textbooks

1) Robert W. Boyd, *Nonlinear Optics (4rd edition)*, Elsevier Academic Press (2020); ISBN 978-0-12-811002-7; freely available online 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; freely available online within USC internet 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; freely available online within USC internet 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; freely available online 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 (from 8 out of 9 problem sets with the lowest grade dropped; 5% each)
15% Midterm Exam
20% Project (10% write-up, 10% presentation)
25% Final Exam

Problem Sets Description & Policy

- There will be 9 weekly problem sets. The one with the lowest grade will be dropped automatically.
- **Problem sets will be posted on Blackboard on Fridays and are due at 3:00pm the following Friday, to be submitted on Blackboard under the Assignments tab.** Solution will be posted on Blackboard on the due date, after lecture.
- **No late submission**, since solution will be posted. Late or no submission result 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 do all of the problems independently.
- You may not copy the problem solutions from anybody else or from any existing solution. If found doing so, you'll receive 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 the 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 time-line:
  - Wednesday, March 10: Project description given.
  - Friday, March 26: Project topic picked.

    - Friday, April 23: Project write-up due by end of day.
    - **Wednesday, April 28 3:00-4:50pm: 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.
- **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 + 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) 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 Feb 5 (the last day to drop a class without a W on the transcript).**

Exam Description & Policy

- **Midterm Exam: 8am Friday 3/19 – 8am Saturday 3/20.**
- **Final Exam: 8am Monday 5/10 – 8am Tuesday 5/11.**
- The exams will be posted on Blackboard under the Exams tab, available at the starting time of the exam. They will be due 24 hours later, to be submitted by uploading a PDF of your solution under the Exams tab.
- These are open-book exams. You are allowed to use: your note, all materials on Blackboard (includes notes and recordings), Boyd's textbook, and Agrawal's textbook. No searching on the internet, and obviously no working together or asking people for help. You will be asked to sign an honor code.
- The exam durations are made to be 24 hours to accommodate students taking the class from different time zones. They should only take you a few hours to finish.
- The scope of the midterm includes all materials up to the midterm. The scope of the final includes all materials over the semester.
- I will be on Zoom to answer questions; you can also email me.
- **If you cannot make the scheduled time of the midterm or final, you must notify and discuss with the instructor before Feb 5 (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 and TA.

Grading Timeline

Problem sets, exams, and project write-up will be graded within two weeks of collection.

Course Schedule (28 classes, including 1 for midterm and 1 for final project presentation)

Date	Topic	Reading
Week 0 1/15	Course info, objectives, and overview. Linear vs nonlinear optics. Superposition principle & light-light interaction. Coupling/decoupling of frequencies.	Boyd 2.1, 1.1
Week 1 1/20, 1/22	Drude-Lorentz model. Anharmonic oscillator. Overview of nonlinear processes. HW 1 assigned.	Boyd 1.4.1, 1.2
Week 2 1/27, 1/29	Susceptibility tensors. Spatial symmetries of $\chi^{(1)}$ and $\chi^{(2)}$. Permutation symmetries. Contracted notation. HW 1 due. HW 2 assigned.	Boyd 1.3, 1.5 Butcher 5.3
Week 3 2/3, 2/5	Effective nonlinear coefficients. Maxwell's equations with nonlinear polarizability. Sum frequency generation (SFG) without pump depletion. Phase matching concept. HW 2 due. HW 3 assigned.	Dmitriev 2.10 Boyd 2.1, 2.2
Week 4 2/10, 2/12	Ordinary & extraordinary rays. Walk off. Type I and Type II phase matching. Noncritical phase matching. Quasi-phase matching. HW 3 due. HW 4 assigned.	Butcher 7.1 Boyd 2.3, 2.4
Week 5 2/17, 2/19	Coupled nonlinear wave equations. Manley-Rowe relations. SFG with partial pump depletion. Second harmonic generation with pump depletion. HW 4 due. HW 5 assigned.	Boyd 2.5, 2.6, 2.7
Week 6 2/24, 2/26	Tensor nature of $\chi^{(3)}$. Intensity dependent refractive index and its polarization dependence. $\chi^{(3)}$ from bound electrons, thermal effects, and in semiconductors. HW 5 due. HW 6 assigned.	Boyd 4.1, 4.2, 4.3, 4.5, 4.6
Week 7 3/3, 3/5	Nonlinear Schrodinger equation (NLSE). Gaussian beams. Self-focusing v.s. diffraction. Spatial soliton: qualitative picture, solution in 1+1D and 1+2D, and stability. HW 6 due. HW 7 assigned.	Boyd 2.10, 7.1 Agrawal 3.1, 5.2.2
Week 8 3/10	Project description. Numerical solution of NLSE with split-step Fourier method. Higher-order solitons. Soliton perturbations & interactions. Filamentation. 3/12: USC Wellness Day; no class HW 7 due.	Boyd 7.1 Agrawal 2.4
Week 9 3/17, 3/19	Review. Midterm Exam: 8am Friday 3/19 – 8am Saturday 3/20	
Week 10 3/24, 3/26	Temporal solitons. Pulse propagation, group velocity, and group velocity dispersion. Instantaneous frequency. Fiber modes. Nonlinear Maxwell's equations for pulse envelopes. Project topic due. HW 8 assigned.	Boyd 7.5 Agrawal 2.2, 2.3
Week 11 3/31, 4/2	Equivalence between spatial and temporal solitons. Modulation instability. Stimulated scattering processes. Stimulated Raman scattering (SRS). Coherent anti-Stokes Raman scattering (CARS). HW 8 due. HW 9 assigned.	Boyd 10.3, 10.5
Week 12 4/9	4/7: USC Wellness Day; no class Raman gain and its threshold. Electrostriction. HW 9 due.	Agrawal 8.1.2 Boyd 9,2
Week 13 4/14, 4/16	Stimulated Brillouin scattering (SBS). Brillouin gain, its threshold, and effect on fiber optic communications. Raman	Boyd 9.3, 11.1 Agrawal 9.2.1

	lasers and Brillouin lasers. Electrooptic (EO) effect: Pockels effect and Kerr EO effect.	
Week 14 4/21, 4/23	EO phase and intensity modulators. Optical phase conjugation. Review Project write-up due on Friday 4/23 by end of day.	Boyd 11.3, 7.2
Week 15 4/28	In-class project presentations on Wed 4/28. 4/30: USC Wellness Day; no class	
Final Week	Final Exam: 8am Monday 5/10 – 8am Tuesday 5/11.	

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.