USC Viterbi
School of Engineering

EE531: Nonlinear Optics

Units: 3

Term: Spring 2020

Lecture: Tue. Thu., 3:30-4:50 PM

Instructor: Chia Wei (Wade) Hsu
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Office Hours: Wed 4:00-6:00 PM

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

All assignments, solutions, handouts, announcements, and grades will be posted on Blackboard.

Exam Dates:

- **Midterm:** Thursday, March 12, 3:30–4:50 PM
- **Final Exam:** Tuesday, May 12, 2:00 PM – Wednesday, May 13, 2:00 PM

Course Description

While the interactions between light and matter are typically linear—twice the input yields twice the response—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 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, and nonlinear spectroscopies. Nonlinear optics is also an important tool for metrology, sensing, quantum optics, and beyond.

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 from anharmonic oscillator. Kramers–Kronig relations. Tensors. Spatial symmetries of linear and nonlinear susceptibilities. Permutation symmetries. Effective nonlinear coefficients. Sum and difference frequency generation. Harmonic generation. Phase-matching and quasi-phase matching. Manley–Rowe relations. Kerr effect. Self-focusing. Spatial solitons. Filamentation and instability. Four-wave mixing. Nonlinear pulse propagation. Temporal solitons. Modulation instability. Stimulated Raman scattering (SRS). Coherent anti-Stokes Raman spectroscopy (CARS). Electrostriction. Stimulated Brillouin scattering (SBS). Electrooptic modulation.

Learning Objectives

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

- understand the origin of nonlinear susceptibilities and their properties;
- predict the frequencies generated by a nonlinear optical process;
- solve nonlinear wave equations in simple problems;
- apply phase matching to enhance nonlinearity;
- explain the origin of spatial and temporal solitons;
- understand stimulated Raman and Brillouin scattering;
- estimate the upper bound of optical power in silica fiber due to nonlinearity;
- apply electrooptic effect for modulations

Prerequisite(s): EE470
Recommended Preparation: Familiarity with Maxwell's equations

Required Readings Textbook

1) Robert W. Boyd, *Nonlinear Optics (3rd edition)*, Elsevier Academic Press (2007); ISBN 9780123694706; freely available online with USC account at https://www-sciencedirect-com.libproxy1.usc.edu/book/9780123694706/nonlinear-optics
A partial errata: http://www.boydnlo.ca/wp-content/uploads/2019/02/Errata-Boyd-NLO.pdf

Supplementary Materials

1) Govind Agrawal, *Nonlinear Fiber Optics (5th edition)*, Elsevier Academic Press (2013); ISBN 978-0-12-397023-7; freely available online within USC internet at https://www.sciencedirect.com/book/9780123970237/nonlinear-fiber-optics

2) Y. R. Shen, *The Principles of Nonlinear Optics*, Wiley, NY (2002); ISBN 978-0-471-43080-3.

3) 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

4) 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

5) Fredrik Jonsson, *Lecture Notes on Nonlinear Optics* (2003); online material, available at http://jonsson.eu/research/lectures

6) NPTEL *Nonlinear Optics* Course (2015); online material, available at https://nptel.ac.in/courses/115101008/

Grading Breakdown

There will be 10 problem sets (the one with the lowest grade will be dropped), one project (with a write-up component and an in-class presentation component), one midterm exam, and one final exam. Details below.

45% Problem sets (from 9 out of 10 problem sets with the lowest grade dropped; 5% each)
15% Midterm Exam
20% Project (10% write-up, 10% presentation)
20% Final Exam

Problem Sets Description & Policy

- There will be 10 weekly problem sets. The one with the lowest grade will be dropped automatically.
- **Problem sets will be posted on Blackboard on Thursdays and are due the following Thursday at the beginning of the lecture (collected in class).** 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; the correct answer alone is worth only partial credit.
- You are encouraged to discuss problems and solution strategies with your classmates, the TA, and/or the instructor. However, each person is expected to do all of the problems independently.
- You may not copy the problem solutions from anybody else or from any existing solution.
- 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.

Project Description & Policy

- There will be one project. The student selects a special topic in nonlinear optics (can be based on recent publications and/or research interests), writes a term paper on the topic, and presents it in class during the last week of class. The instructor will provide guidance for the selection of topic.
- Project time-line:
    - Tuesday, March 10: Project description given.
    - Thursday, March 26: Project topic picked.
    - Thursday, April 23: Project write-up due.
    - Tuesday, April 28 & Thursday, April 30: In-class presentations.
- The write-up and the presentation each count toward 10% of the course grade.
- The write-up should be 2-4 pages, in the style of a single-spaced double-column journal paper.
- Each presentation will be max 10 minutes + 2 minutes for questions.

Exam Description & Policy

- 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. => Due to the COVID situation, exams now become open-book take-home exams.
- If you cannot make the scheduled date/time of the final exam, you must notify the instructor before the last day to add/drop. If the instructor cannot accommodate your schedule, you must drop the class.
- In the case of a medical emergency, a signed letter from your doctor is required. This letter must include the telephone number of your doctor.
- For requests for accommodations due to disabilities, provide letter from the Office of Disability Services and Programs (DSP) to the instructor and TA.

Grading Scale

The raw grades may be subject to a curve, based on the student score distribution and the discretion of the instructor, before a final grade is assigned.

Grading Timeline

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

Course Schedule: A Weekly Breakdown

Date	Topic	Reading
Week 1	Maxwell's equations. Definition of linear/nonlinear optics. Superposition principle. Monochromaticity. Drude-Lorentz model. Anharmonic oscillator. Nonlinear susceptibilities. HW 1 assigned.	Boyd 2.1, 1.1, 1.4
Week 2	Overview of nonlinear processes. Second-order: SHG, optical rectification, SFG, DFG/OPA, OPO & HHG; Third order: 3HG, Kerr effect, two-photon absorption, FWM. Saturable absorption. Gain saturation. Stimulated Raman scattering. Stimulated Brillouin scattering. HW 1 due. HW 2 assigned.	Boyd 1.2, 1.3
Week 3	Tensor nature of linear and nonlinear susceptibilities. Absence of $\chi^{(2)}$ in centrosymmetric systems. Spatial symmetries and crystal classes. Constraints on the $\chi^{(1)}$ and $\chi^{(2)}$ tensors due to spatial symmetries; KDP example. Birefringence and waveplates. HW 2 due. HW 3 assigned.	Boyd 1.5
Week 4	Rotation matrices. Neumann's principle. Partial permutation symmetry and contracted notation. Full Permutation symmetry and Kleinman's symmetry. Effective nonlinear coefficients. Maxwell's equations with nonlinear polarizability. SFG without pump depletion. Phase matching. HW 3 due. HW 4 assigned.	Boyd 2.1, 2.2
Week 5	Coherent length and oscillation of SFG output. Ordinary ray and extraordinary ray in uniaxial material. Type I and Type II angular phase matching using birefringence. HW 4 due. HW 5 assigned.	Boyd 2.3
Week 6	Quasi-phase matching and periodic poling. Coupled nonlinear wave equations. Manley-Rowe relations. Up-conversion and down-conversion. HW 5 due. HW 6 assigned.	Boyd 2.4, 2.5, 2.6
Week 7	Tensor nature and polarization dependence of $\chi^{(3)}$. Kerr effect and intensity dependent refractive index. Self-focusing and the threshold power. HW 6 due. HW 7 assigned.	Boyd 4.1, 4.2, 7.1
Week 8	Self-trapping and spatial solitons. Spatial four-wave mixing. Filamentation and beam breakup. Bespalov-Talanov instability. HW 7 due.	Boyd 7.1
Week 9	Review. Project description. Midterm Exam.	
Spring Break		
Week 10	Pulses and time-domain description. Group velocity and group velocity dispersion. Instantaneous frequency. Qualitative picture of temporal solitons. Nonlinear Maxwell's equations for pulse envelopes. Project topic due. HW 8 assigned.	Boyd 7.5
Week 11	Pulse envelope equations in retarded frame. Mathematical equivalence between a temporal soliton and a 2D spatial soliton. Soliton stability. Modulation instability. Basic concepts of stimulated Raman scattering (SRS) and stimulated Brillouin scattering (SBS). HW 8 due. HW 9 assigned.	Boyd 10.3

Week 12	Nonlinear polarization and SRS from vibrational modes. Raman gain and its threshold. Electrostriction. HW 9 due. HW 10 assigned.	Boyd 10.3, Agrawal 8.1.2, Boyd 9,2
Week 13	Nonlinear polarization and SBS from Electrostriction. Phase matching for backward SBS. Brillouin gain, its threshold, and effect on fiber optic communications. Raman lasers. Brillouin lasers. HW 10 due.	Boyd 9.3, Agrawal 9.2.1
Week 14	Coherent anti-Stokes Raman spectroscopy (CARS). Electrooptic effect: Pockels effect and Kerr EO. Electrooptic modulators using KDP. Project write-up due.	Boyd 10.5, 11.1, 11.3
Week 15	In-class project presentations.	
Final Week	Final Exam.	

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.