E566 Optical Information Processing

Units: 4
Term: Fall 2024
Lecture: MW 2:00 - 3:50 PM, LVL 16

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IT Help: for help with USC-supplied software, on-campus networking, or Brightspace access, consult USC ITS at https://itservices.usc.edu/contact/
For help relating to class content, see "Course Notes" below.

Course Description

Our fast changing world requires us to process large-scale information more efficiently and accurately. Using optical signals to carry and process information has advantages of high bandwidth, low loss, energy efficiency and compatibility with communication networks. This course is devoted to analysis, synthesis and application of optical systems for spatial and temporal signal processing, covering methods that are applicable to a wide range of problems as well as related trending topics.

Topics that will be covered include space-time duality, light propagation and diffraction, imaging in space and time, optical Fourier transforming systems, introduction to optical computing systems, holography, nonlinear optics, coherent and incoherent systems, and the emerging directions of optical (shallow and deep) neural networks, large scale integration as well as quantum information processing. In addition, examples of optical processing systems such as optical coherence tomography, optical interconnections in multichip modules, computational imaging, and multidimensional displays, will be included depending on student interest.

In addition to weekly problems sets, we will have midterm and final exams, and a final project with topics chosen by students.

Learning Objectives

Upon successful completion of this course, the student will be able to:

- Characterize propagation and diffraction of coherent light
- Create and analyze coherent and incoherent optical imaging systems
- Understand a wide variety of coherent optical systems
- Evaluate optical free-space systems for information processing
- Apply the fundamentals of holography to create optical components and systems
- Apply Fourier optics in the temporal domain to evaluate and create systems for time-domain signal processing
- Analyze nonlinearity of optical systems and their applications in optical logic gates
- Apply optical modulation methods based on light-matter interactions to optical signal-processing systems
- Understand cutting edge research topics in the field of optical information processing

Prerequisite(s): None.
Co-Requisite(s): None.
Concurrent Enrollment: None.
Recommended Preparation: Continuous-time Fourier transforms, linear systems, and signals/functions at the level of EE 301; programming in MATLAB or Python can be helpful but isn't mandatory.
Relevant but not required: Familiarity with basic electromagnetics.

Course Notes

Piazza will be set up for class collaboration, and will be the primary vehicle for online Q&A with the instructors and TA.
The main website for all course materials can be accessed from:
Brightspace.usc.edu
Course materials (lecture notes and codes prepared by the instructors, handouts, homework assignments and solutions, graded homeworks, etc.) will be available to all registered students at this site.

Technological Proficiency and Hardware/Software Required

Some students may choose to include computer coding as part of their project. If so, MATLAB or Python are recommended.

Required Readings and Supplementary Materials

Course texts and other resources (required)

- Joseph W. Goodman, *Introduction to Fourier Optics*, Fourth Edition (W. H. Freeman and Company, New York, 2017)
- Bahaa E.A. Saleh, Malvin Carl Teich, *Fundamentals of Photonics Vol. 2*, Wiley, Third edition (2019)
- Victor Torres-Company, Jesus Lancis, Pedro Andres, "Chapter1 - Space-Time Analogies in Optics", P*rogress in Optics 56*, 2011, Page 1-80 (Available for download from USC library online resources)
- Reza Salem, Mark A. Foster, and Alexander L. Gaeta, "Application of space–time duality to ultrahigh-speed optical signal processing," *Adv. Opt. Photon. 5*, 274-317 (2013) (Available from USC library online resources)

Description and Assessment of Assignments

Homework assignments. There will be approximately one homework assignment per week, for most weeks. Each homework assignment will be posted on Brightspace, and each student will submit their solution by uploading a pdf file to Brightspace.

Midterm exam will be Wednesday Oct. 23, 2024, during regular lecture time 2:00 – 3:50 PM.
Final exam is scheduled by the university and will take place on Friday, Dec. 13, 2024, 2:00 – 4:00 PM.

Attendance in person is required for both exams; the only exceptions will be due to documented medical or other emergency situations.

Final project. There will be one final project, starting in Week 10 and ending in Week 15. It is described after the course outline below.

Grading Breakdown (tentative)

Item	
Homework	25%
Midterm exam	25%
Final exam	25%
Final project	20%
Class participation (online and in class)	5%

Grading Scale
The course will be graded on the curve.

Assignment Submission Policy
- All assignments will be submitted on Brightspace
- Late Policy to be announced.

Grading Timeline
Graded assignments will be returned as soon as possible, usually ~2 weeks after submission.

Additional Policies

For policy on collaboration and use of AI Tools in this class, please see statements below (after the list of Sample Applications).

Course Outline

Lectures 1-13

i. Course introduction

- Course logistics and requirements; course overview 1 [Jenkins]
- Course overview 2; sample applications [Jenkins and Yu]

ii. Background material and review [Jenkins]

- Delta functions
- Linear systems
- Fourier transforms (2-D)
- Space-bandwidth and time-bandwidth products; local spatial frequency

iii. Scalar diffraction theory and wavefront propagation [Jenkins]

- Preliminaries (representation, scalar diffraction theory assumptions)
- Wave and Helmholtz equations
- Formulation of optical waves
- Diffraction during propagation - spatial-frequency domain (Angular spectrum of plane waves)
- Definition and modeling of (passive) optical components
- Diffraction during propagation - spatial domain (Monochromatic and nonmonochromatic cases)
- Analysis of optical systems (spatial domain, Fourier domain, hybrid)
- *Evanescent waves and negative index materials (metamaterials)

iv. Approximations to diffraction [Jenkins]

- Initial approximations (of Rayleigh-Sommerfeld formula)
- Fresnel (near to far field, paraxial)
- Fraunhofer (far field, paraxial)
- *Limited spatial frequency
- Example 1: absorption and phase gratings; diffraction efficiency
- Example 2: photonic interconnections in multichip modules
- *Example 3: diffractive optical elements – computer designed to synthesize arbitrary diffraction patterns

vi. Thin lenses and optical imaging systems [Jenkins]

- Thin lenses
- Coherent Imaging systems
- Generalized imaging systems
- Frequency-domain analysis
- Coherent illumination and coherent transfer function (CTF)

v. Topic(s) to be chosen, from: [Jenkins]

- Coherence
- Imaging in incoherent light
- Holography
- Introduction to 3D displays

Lectures 14-16

vii. Optical Fourier transforming and imaging using thin-lens systems [Yu]

=> Assume coherent illumination
– Fourier transforming
– *Research example: superlenses to exceed the diffraction limit
– General optical system analysis

viii. Space-time duality [Yu]

– Space-time analogy: diffraction and dispersion
– Time lens and its implementation
– Temporal processing, imaging, and waveform generation in coherent and incoherent optical systems

ix. Optical modulation [Yu]

– Acousto-optics
– Electro-optics
– All-optical interaction

Lecture 17

x. Course project description and topics [Yu and Jenkins]

xi. Review for midterm exam [Jenkins]

Lectures 18-26

xii. Nonlinear optics [Yu]

– Nonlinear optics in information processing and computing: nonlinear optic gate, single photon nonlinearity, phase conjugation, ultrafast optics

xiii. Information processing: optical/photonic devices and systems [Yu]

– Coherent processing systems (including frequency domain processing)
– Incoherent processing systems
– Application examples: Fourier-domain filtering; deep convolutional neural networks

xv. Emerging directions in optical information processing [Yu]

– Photonic artificial neural network/machine learning
– Photonic quantum information processing
– Go smaller: meet with nanophotonic circuits
– Optical frequency combs
– New photonic materials: metamaterials (flat lens), phase-change material and 2D materials

Lecture 27

xvi. Logistics for final exam and project presentations [Jenkins and Yu]

xvii. Reviews [Yu and Jenkins]

xviii. Student project presentations 1 [Jenkins and Yu, moderators]

Lecture 28

xix. Student project presentations 2 [Jenkins and Yu, moderators]

Final Project Description

Students will be divided into teams of two, by self-selecting partners (primarily) or with the help of instructors (where needed). Each student team will choose their own project topic, with help from the instructors and TA.

We describe 4 example project topics as follows. (i) "All optical quantum computing based on single photon nonlinearity", in which students can apply both nonlinear optics and nanophotonics to figure out the parameters or device architectures for achieving a two-photon gate, and explain its significance to building a universal photonic quantum computer. (ii) "Temporal cloaking" which uses the Fourier optics in the temporal domain to explain how to create a temporal "hole". Students are expected to summarize different approaches (for example, based on four-wave mixing or electro-optic effects, which are covered in the course). (iii) "Diffractive optical element (DOE) design" in which students design by computer a DOE for a specific purpose, and evaluate its performance numerically; effects of quantization can also be evaluated. (iv) "Numerical simulation of beam propagation behind a component in free space". (iii) and (iv) require some knowledge of sampling.

Proposal. Each group will submit a 1-page project proposal, including: title, authors, email contact; goals of the project; description of their intended approach; and any references.

Presentation and final report. Each group will give a 15-min. presentation to the class, and write a report which is 4 pages maximum in length in a format of a single-spaced double-column paper. The targeted audience is the fellow classmates. Each presentation is followed by a 3-min Q&A.

Final project timeline.

- Week 10: form groups, pick a topic, submit project proposals, and discuss with the instructor.
- Week 15, during lecture periods: final project presentations.
- Last day of Week 15: final reports due.

Originality in the project is a bonus, but not required. Students are encouraged to propose new ideas with some simulation or analysis for support, reproduce results from a recent paper (codes or related files should be included), or do interdisciplinary exploration.

Sample Applications (Past, Current, and Future)

=> We will choose a few of these to discuss in class

1. Optics and diffraction effects in the eye
    - What is actually incident on the retina
    - Effects of coherence, pupil size and shape
2. Signal processing and computing
    - Special-purpose parallel signal processing
    - Optical interconnections
        - Board-to-board, chip-to-chip, within-chip
    - Large-scale artificial neural network processing
3. Photonic quantum information processing
    - Quantum theory of light: Photon as flying qubits
    - Quantum communications with photons
    - Quantum computation with single photons (linear quantum computing, single photon nonlinearity, atomic-photon interfaces, etc.)
4. Optical metamaterials
    - Index of refraction $n < 1$ and $n < 0$
    - Superlenses
    - Cloaking devices
5. Biomedical applications
    - Optical coherence tomography
    - Infrared optical techniques for brain imaging
    - Probing of micro-array-experiment data
6. Displays
    - 3-D displays based on integral imaging
    - True 3-D displays based on holography
    - Multiplane displays based on computer holography
    - True 3-D displays based on filled volume techniques
    - Head-mounted displays for virtual reality and augmented reality
7. Image acquisition
    - Camera optics (e.g., in smartphones)
    - 3D image acquisition
    - Lidar
        - Sensing surroundings for self-driving cars
        - Remote sensing of the environment
8. Diffractive optical components and systems
    - Diffractive optical elements (DOE's) for generation of arbitrary output intensity or phase patterns
    - Holographic optical elements for generation of arbitrary point-spread functions

- Examples
  - Diffractive optical concentrators for solar cells
  - Free-space or substrate-mode optical interconnections

9. Non-invasive inspection, test, and measurement
   - Holographic-interferometric measurement of distances and surface shape variations
   - Inspection of integrated circuits after fabrication
   - Measurement of surface warping due to stress and strain
     - Mechanical systems in automobiles, aircraft, and spacecraft
     - Optimize strength, durability, weight
   - Test of VLSI circuit function using optical access (input and output of test signals)

Collaboration and Use of AI Tools

Collaboration and individual work

Collaboration on techniques for solving homework assignments is allowed, and can be helpful; however, each student is expected to work out and write up his or her own solution. Use of other solutions to homework assignments, from any source including other students, before the assignment is turned in, is not permitted.

For class projects, general collaboration to resolve issues, or to clarify technical material, is allowed. Use of internet as well as journal and conference literature is encouraged. However, each student (or team) does their own work and writes up their own report. The author(s) of the report are presenting themselves as having done the work described in the report. Any reported work, explanations, or other information that is obtained from others must be cited as such. Including such work in the report without citing its source amounts to plagiarism.

Please also see the paragraph on "Academic Conduct" below (last 2 pages of syllabus) for additional policies that apply to all USC classes.

Use of Artificial Intelligence (AI) Tools including generative AI

The ability to think creatively and originally, as well as analytically and critically, are important parts of learning in this class and in science and engineering generally. Learning from other resources can also help you acquire knowledge. In order to balance these approaches, in this class we will encourage and enforce the following policy on use of AI tools (such as generative AI tools like ChatGPT and other AI assistants).

Appropriate use of AI tools. In exploring concepts and approaches in this class, you may find it useful to look online for information. This may include posing questions to a generative AI tool. In doing this, it is recommended to first consider the question yourself (or yourself and a few classmates in a learning group); the ability to explore new ideas or questions, and analyze them critically and creatively, are important skills to acquire, and these are best acquired by trying. After some of this analysis and thinking, you may find it useful to consult a generative AI tool to see it's response. Keep in mind that any generative AI response may sound convincing initially but may in fact be wrong, so analyzing its response will also need some critical thinking on your part.

Inappropriate use of AI tools. Use of these tools to solve homework problems, exam or exam-assignment problems, or do some of the work of you course project, are prohibited. These assignments and projects are intended to help you learn the course material by having you think through how to solve a problem or analyze a result. In the case of exams, they are designed to assess what you have learned and what you are capable of doing on your own. In both cases, use of AI tools will shot-circuit the intended purpose. This inappropriate

use of AI tools amounts to plagiarism (using the AI tool's results as part of the work you are representing as your own work); when detected, this will result in penalties due to violations of academic integrity.

What about your future? Consider any of the following scenarios that are likely in your future: (i) you are interviewing for a job or for a PhD program; (ii) you are in your first job, presenting results of your work to your supervisor in person, and your supervisor is asking you questions about your work (e.g., how did you do this part; which method did you use for that part); (iii) you are presenting a proposal of future directions to take (to management at a company, or to funding agents for future research to pursue in academia or in a research lab), and they ask questions about your proposal during the presentation; (iv) you are giving a talk at a conference about work you have done, and people ask you probing questions about the work you did. In all these scenarios, you do not have the option of asking an AI tool before responding to the questions you are asked; you have to be able to develop an answer from your own knowledge and thinking ability.

Coding. While some generative AI tools are pretty good at coding, there is still the need for a person to check the code for accuracy and correctness, and especially to understand how the problem is being solved by the code provided (for example, to know in what cases the resulting outputs will be valid). So the person using the code must understand how to code well to be able to use the code reliably.

In this class:

- AI tools including generative AI can help you learn if used in an appropriate way.
- AI tools can be a crutch that prevents you from learning if used excessively or in an inappropriate way.
- In this class using AI Tools in the following ways is prohibited and amounts to plagiarism:
    - to obtain results that you report on as part of any of your work (including homework and project work), without clearly stating that an AI Tool was used, including how it contributed, to what results it contributed, and what you did on your own;
    - to solve any assigned work except where explicitly stated as allowed;
    - to write any portion of your assigned solutions to homeworks or exams, even if you modify the AI tool's answers somewhat.

Statement on Academic Conduct and Support Systems

Academic Integrity:
The University of Southern California is a learning community committed to developing successful scholars and researchers dedicated to the pursuit of knowledge and the dissemination of ideas. Academic misconduct, which includes any act of dishonesty in the production or submission of academic work, compromises the integrity of the person who commits the act and can impugn the perceived integrity of the entire university community. It stands in opposition to the university's mission to research, educate, and contribute productively to our community and the world.

All students are expected to submit assignments that represent their own original work, and that have been prepared specifically for the course or section for which they have been submitted. You may not submit work written by others or "recycle" work prepared for other courses without obtaining written permission from the instructor(s).

Other violations of academic integrity include, but are not limited to, cheating, plagiarism, fabrication (e.g., falsifying data), collusion, knowingly assisting others in acts of academic dishonesty, and any act that gains or is intended to gain an unfair academic advantage.

The impact of academic dishonesty is far-reaching and is considered a serious offense against the university. All incidences of academic misconduct will be reported to the Office of Academic Integrity and

could result in outcomes such as failure on the assignment, failure in the course, suspension, or even expulsion from the university.

For more information about academic integrity see the student handbook or the Office of Academic Integrity's website, and university policies on Research and Scholarship Misconduct.

Please ask your instructor if you are unsure what constitutes unauthorized assistance on an exam or assignment, or what information requires citation and/or attribution.

Students and Disability Accommodations:

USC welcomes students with disabilities into all of the University's educational programs. The Office of Student Accessibility Services (OSAS) is responsible for the determination of appropriate accommodations for students who encounter disability-related barriers. Once a student has completed the OSAS process (registration, initial appointment, and submitted documentation) and accommodations are determined to be reasonable and appropriate, a Letter of Accommodation (LOA) will be available to generate for each course. The LOA must be given to each course instructor by the student and followed up with a discussion. This should be done as early in the semester as possible as accommodations are not retroactive. More information can be found at osas.usc.edu. You may contact OSAS at (213) 740-0776 or via email at osasfrontdesk@usc.edu.

Support Systems:

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

988 Suicide and Crisis Lifeline - 988 for both calls and text messages – 24/7 on call
The 988 Suicide and Crisis Lifeline (formerly known as the National Suicide Prevention Lifeline) provides free and confidential emotional support to people in suicidal crisis or emotional distress 24 hours a day, 7 days a week, across the United States. The Lifeline is comprised of a national network of over 200 local crisis centers, combining custom local care and resources with national standards and best practices. The new, shorter phone number makes it easier for people to remember and access mental health crisis services (though the previous 1 (800) 273-8255 number will continue to function indefinitely) and represents a continued commitment to those in crisis.

Relationship and Sexual Violence Prevention Services (RSVP) - (213) 740-9355(WELL) – 24/7 on call
Free and confidential therapy services, workshops, and training for situations related to gender- and power-based harm (including sexual assault, intimate partner violence, and stalking).

Office for Equity, Equal Opportunity, and Title IX (EEO-TIX) - (213) 740-5086
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.

Reporting Incidents of Bias or Harassment - (213) 740-5086 or (213) 821-8298
Avenue to report incidents of bias, hate crimes, and microaggressions to the Office for Equity, Equal Opportunity, and Title for appropriate investigation, supportive measures, and response.

The Office of Student Accessibility Services (OSAS) - (213) 740-0776
OSAS ensures equal access for students with disabilities through providing academic accommodations and auxiliary aids in accordance with federal laws and university policy.

USC Campus Support and Intervention - (213) 740-0411
Assists students and families in resolving complex personal, financial, and academic issues adversely affecting their success as a student.

Diversity, Equity and Inclusion - (213) 740-2101
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
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) 442-1200 – 24/7 on call
Non-emergency assistance or information.

Office of the Ombuds - (213) 821-9556 (UPC) / (323-442-0382 (HSC)
A safe and confidential place to share your USC-related issues with a University Ombuds who will work with you to explore options or paths to manage your concern.

Occupational Therapy Faculty Practice - (323) 442-2850 or otfp@med.usc.edu
Confidential Lifestyle Redesign services for USC students to support health promoting habits and routines that enhance quality of life and academic performance.