E566 Optical Information Processing
Units: 3 or 4*
Term: Spring Semester

Lecture: Tue. Thu., 5:00-6:50 PM
Breakout session: One 50-minute session in most weeks, to be scheduled (led by TA)

Location: GFS 228 (Students that cannot attend for health or safety reasons will be accommodated.)

Instructor: Prof. B. Keith Jenkins
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Instructor: Prof. Mengjie Yu
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Office Hours: TBD
Contact Info: TBD

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

*For this newly revised class, you can choose 3 units or 4 units, as follows.

For a 3-unit class:

- Register for EE 566 (3 units) only (no EE 590/790). Take the full class as offered, but omit the course project. You do not need to attend (but may optionally attend if you choose): (i) any breakout sessions that cover only the project; (ii) the lecture periods (or portion of lecture periods) that consist of student project presentations.

For a 4-unit class:

- To get credit for the full 4 units, register for EE 566 (3 units) and for 1 unit of EE 590 or EE 790 with either Prof. Jenkins or Prof. Yu; please state in your EE 590/790 request, as your topic or description, "EE 566 project".
- All portions of the class are required (unless stated otherwise), including the course project.

- Upon successful completion of the class, you will have 4 units of course credit (3 units of letter grade for EE 566 and 1 unit of CR for EE 590/790).

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. .

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:

blackboard.usc.edu

Course materials (lecture videos, 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

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

There will be one final project, starting in Week 9 and ending in Week 15. It is described after the course outline below.

Grading Breakdown (tentative)

Item	**4-unit class**	**3-unit class**
Homework	30%	40%
Midterm exam	25%	30%
Final exam	25%	30%
Final project	20%	0%
Class participation (online and in class) (bonus points)	5%	5%

Grading Scale

The course will be graded on the curve.

Assignment Submission Policy

- All assignments will be submitted on Blackboard
- Late Policy to be announced.

Grading Timeline

Graded assignments will be returned as soon as possible, usually 1-2 weeks after submission.

Course Outline

Lectures 1-16

1. Course introduction

   – Course logistics and requirements
   – Overview of course material and sample applications

2. Background material and review

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

3. Scalar diffraction theory and wavefront propagation

   – 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)

4. Approximations to diffraction

   – 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

5. Optical Fourier transforming and imaging using thin-lens systems

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

6. Coherence

   – Spatial and temporal coherence
   – Coherent and incoherent illumination
   – *Biomedical application example: Optical coherence tomography for 3-D imaging

Lectures 17-20

7. Optical modulation and nonlinear optics

- Acousto-optics
- Electro-optics
- All-optical interaction
- Nonlinear optics in information processing and computing: nonlinear optic gate, single photon nonlinearity, phase conjugation, ultrafast optics

8. Space-time duality (final project topic due)

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

Lectures 21-24

9. Optical imaging systems (generalized)

- Frequency-domain analysis of generalized imaging systems
- Coherent illumination and CTF
- Incoherent illumination and OTF
- *Application example: diffraction effects in the eye

10. Information processing: optical/photonic devices and systems

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

11. Introduction to holography

- Wavefront recording and reconstruction
- Planar holography (for 3-D reconstruction and general wavefront reconstruction)
- Application example 1: pictorial holography
- *Application example 2: true 3-D displays
- *Computer-generated holography
- *Volume holography

Lectures 25-26

12. Emerging directions in optical information processing

- 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 27-28 (as time permits)

13. **Other topics and applications of interest

Lectures 28-29

14. Student project presentations

*Inclusion of indicated topics will depend on time available and student interest.

** ”Other topics and applications of interest” will be chosen from:

- Spatial superlenses to exceed the diffraction limit
- Spatial cloaking using metamaterials
- True 3D displays
- Computer-generated holography
- Lidar and 3D data acquisition
- Quantum communication network with photons
- Temporal-frequency-domain information processing
- Other topics suggested by students

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 3 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.

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 5-min Q&A.

Final project timeline.

- Weeks 9-10: 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)

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 Research and Scholarship Misconduct.

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

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 for Equity, Equal Opportunity, and Title for appropriate investigation, supportive measures, and response.

The Office of Student Accessibility Services (OSAS) - (213) 740-0776
osas.usc.edu
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) 821-4710
campussupport.usc.edu
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
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.

Office of the Ombuds - (213) 821-9556 (UPC) / (323-442-0382 (HSC)
ombuds.usc.edu
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) 442-33*40 or otfp@med.usc.edu
chan.usc.edu/otfp
Confidential Lifestyle Redesign services for USC students to support health promoting habits and routines that enhance quality of life and academic performance.