OPTI 647: Photonic Quantum Information Processing Effective Fall Semester 2022

Course Description:

Photonic quantum information processing is a field that investigates the use of non-classical sources, processing and detection of light that could help encode and process information encoded in photons much more efficiently compared to conventional methods, with applications in optical communications, security, sensing and computation. This course will be aimed at developing a principled understanding of quantum mechanical description of light, its generation, manipulation and detection. This course will be valuable for graduate students who intend to partake in theoretical or experimental research in any area of photonic quantum information processing, such as quantum communications, sensing and computation. In this course we will focus on the mathematical material: modal decomposition of the optical field, semi-classical description of optical detection, develop intuition on why a more powerful (quantum) theory is required to interpret photo-detection statistics of certain forms of non-classical light, leading into the development of the notion of “classical” and “non-classical” states of a collection of optical modes in a formal way, develop the notion of Gaussian and non-Gaussian states, processes and measurements, and the phase-space formalism. We will focus on methods to generate, manipulate and detect interesting non- classical and entangled states of photons, the role and limitations of linear optics, realization of Gaussian transformations (which subsume linear optics and squeezing transformations) and more general non-Gaussian transformations. We will draw specific examples from important applications of photonic quantum information processing. We will also calculate various metrics of quantum states and measurements (e.g., Relative entropy, Fidelity, Fisher information etc.) and their operational meanings in various applications.

Prerequisites:

Excellent knowledge of complex numbers, linear algebra, Fourier transforms, probability and random processes. Prior background in quantum physics is extremely valuable but not required. If a prospective student has not taken any undergraduate or graduate course in quantum physics, prior consultation with the instructor is recommended.

Number of Units: 3

Locations and Times: in-person. Recordings are provided for DL students. Tuesday, Thursday 8am-9.15am.

Instructor Information:

Instructor name: Christos Gagatsos

Office: Meinel 540

Email: cgagatsos@email.arizona.edu

Phone: -

Office hours: Every Wednesday 10-11am

Expected Course Objectives:

- During this course, students will learn how to mathematically describe classical and quantum states of light, how to understand all forms of light in one unified framework.
- During this course, student will learn how certain interesting forms of non-classical light can be generated, how to characterize them mathematically, and how to transform and detect light in novel non-standard ways.
- During this course, students will learn some tools from quantum information and estimation theory to appreciate how leveraging quantum properties of light can help encode and process information more efficiently, and its applications in communications, sensing and computing.

Expected Learning Outcomes:

- Upon completion of this course students will be able to understand the role of quantum theory in describing optical field in the most general way.
- Upon completion of this course students will be able to manipulate the mathematics necessary for quantum information of continuous variable systems.
- Upon completion of this course students will be able to understand the basic principles of non-classical and entangled photonic states, and the physical mechanisms to generate them.
- Upon completion of this course students will be able to understand how to break down. mathematical descriptions of various non-classical optical transformation and detection into structured realization using well-understood optical components
- Upon completion of this course students will be equipped with background to do research in various new directions in quantum enhanced photonic information processing.

Texts, other required or recommended materials

There is no required text but handouts and references will be provided as necessary.

Topics and general calendar:

Roughly one homework assignment will be distributed each week. There will be 2 lectures each week, each 1 hour and 15 minutes long. One pre-scheduled hour-long office hour will be made available every week for 14 weeks. During the 15th week, there will be 2 scheduled hours of final presentations to be made by students.

The topics below are a guideline for the topics that will be covered in the course.

1. Quantum mechanics of photons
    - Annihilation and creation operators and commutators
    - Pure states: Number states, coherent states
    - Mixed states: Thermal states, P-function representation, Q-functions
    - Unitary operations: Displacement, squeezing, beam-splitters

- Measurements: Direct detection, homodyne and heterodyne detection: Quantum and semi-classical descriptions
- Hamiltonian descriptions of various optical components
- Special focus on the mathematics of Gaussian states and operations
- Characteristic functions, Wigner functions and covariance matrices
- Mach-Zehnder interferometer (MZI)
- Decomposition of arbitrary multimode linear optics into MZIs
- Decomposition of arbitrary multimode squeezing transformation
- Generation of arbitrary multimode squeezed pure and mixed states

3. Non-Gaussian states of light

    - Cat states and cat-state superpositions
    - Photon subtraction and addition for heralded generation of non-Gaussian states
    - General schemes of non-Gaussian state engineering based on partial detection
    - Non-Gaussian entangled states

4. Quantum information processing

    - Quantum sensing and metrology: basic introduction and application
    - Quantum communications
    - Quantum/covert communications
    - Quantum/covert sensing

Number of Exams and Papers:

Approximately one homework assignment will be given every week during the semester. In lieu of examinations, students will be required to present their solution of any one of the advanced problems to be provided throughout the semester.

Course Policies:

Grading Policy

Homeworks (roughly one every week) 70%, Final presentation 30%, Total 100%

The grade will be determined in an absolute fashion. Maximum grade is 5, then 5-4.1 = A, 4- 3.1 = B, 3-2.1 = C, 2-1.1: D, 1-0: E.

Code of Academic Integrity

Students are encouraged to share intellectual views and discuss freely the principles and applications of course materials. However, graded work/exercises must be the product of independent effort unless otherwise instructed. Students are expected to adhere to the UA Code of Academic Integrity as described in the UA General Catalog. See: http://deanofstudents.arizona.edu/academic-integrity/students/academic-integrity

According to the Arizona Code of Academic Integrity, “Integrity is expected of every student in all academic work. The guiding principle of academic integrity is that a student’s submitted work must be the student’s own.” Unless otherwise noted by the instructor, work for all assignments in this course must be conducted independently by each student. Co-authored work of any kind is unacceptable. Misappropriation of exams before or after they are given will be considered academics misconduct. Misconduct of any kind will be prosecuted and may result in any or all of the following:

- Reduction of grade
- Failing grade
- Referral to the Dean of Students for consideration of additional penalty, i.e. notation on a

  student’s transcript re. academic integrity violation, etc.

Attendance Policy

It is important to attend all classes, as what is discussed in class is pertinent to adequate performance on assignments and exams. If you must be absent, it is your responsibility to obtain and review the information you missed. This is especially important in this course where a substantial amount of course material will emerge through class discussion.

"All holidays or special events observed by organized religions will be honored for those students who show affiliation with that particular religion. Absences pre-approved by the UA Dean of Students (or Dean's designee) will be honored."

Classroom Behavior Policy

To foster a positive learning environment, students and instructors have a shared responsibility. We want a safe, welcoming, and inclusive environment where all of us feel comfortable with each other and where we can challenge ourselves to succeed. To that end, our focus is on the tasks at hand and not on extraneous activities (e.g., texting, chatting, reading a newspaper, making phone calls, web surfing, etc.).

Threatening Behavior Policy

The UA Threatening Behavior by Students Policy prohibits threats of physical harm to any member of the University community, including to oneself. See http://policy.arizona.edu/education-and- student-affairs/threatening-behavior-students.

Accessibility and Accommodations

At the University of Arizona we strive to make learning experiences as accessible as possible. If you anticipate or experience physical or academic barriers based on disability or pregnancy, you are welcome to let me know so that we can discuss options. You are also encouraged to contact Disability Resources (520-621-3268) to explore reasonable accommodation.

If our class meets at a campus location: Please be aware that the accessible table and chairs in this room should remain available for students who find that standard classroom seating is not usable.

Subject to Change Statement

Information contained in the course syllabus, other than the grade and absence policy, may be subject to change with advance notice, as deemed appropriate by the instructor.