THE UNIVERSITY OF ARIZONA

SYLLABUS

OPTI 495B/595B: Information in a Photon (3 units)

Fall 2025

Mondays/Wednesdays: 3:30 – 4:45 PM

Meinel 307

Description of Course

This course develops the mathematical theory of noise in optical detection from first principles, aiming to understand the fundamental limits of efficiency in extracting information encoded in light. We will explore how interferometric manipulations of the information-bearing light in the optical domain—prior to actual detection—can alter post-detection noise statistics. Additionally, we will examine how detection-induced electro-optic feedback during the detection process can further modify these statistics favorably, thereby improving the efficiency of information extraction.

Throughout the course, we will evaluate applications of these novel optical detection methods in optical communications and sensing, comparing their performance with conventional light detection techniques. We will also compare the performance of these methods to the theoretical maximum achievable in the given context, as governed by the laws of quantum physics, without providing explicit derivations of those fundamental quantum limits.

The primary goal of this course is to equip students—as well as interested postdocs and faculty from diverse backgrounds—who are considering theoretical or experimental research in quantum-enhanced photonic information processing with deeper insights into optical detection. We aim to develop an appreciation for: (1) The value of a full quantum treatment of light to find the fundamental limits of encoding information in photons, (2) How pre-detection manipulation of information-bearing light can favorably dispose the information with respect to inevitable detection noise.

This course does not assume any background in optics, stochastic processes, quantum mechanics, information theory, or estimation theory. However, an undergraduate-level mathematical background and proficiency in complex numbers, probability theory, and linear algebra (vectors and matrices) are assumed.

Course Prerequisites or Co-requisites

1. Complex numbers
2. Basic probability theory
3. Elementary linear algebra

[This course should be accessible to most senior undergraduate and graduate students. Basic exposure to and proficiency in undergraduate mathematics will be assumed. If unsure, please contact instructor prior to registering.]

Instructor and Contact Information

Instructor name: Daniel Soh, Office: GCRB 441 Email: danielsoh@arizona.edu

Instructor Office hour - by email appointment only

TA Office hour- TBD.

Course Format and Teaching Methods

Lectures and office hours, on campus only

Course Objectives and Expected Learning Outcomes

This course straddles all four tracks at the College of Optical Sciences. It will introduce photonic quantum information processing to a broad audience in a way accessible to students (as well as interested postdocs and faculty) in optical physics, photonics, image science and optical engineering. The goal of this course is to provide a starting point for launching into research on quantum enhanced photonic information processing, tied to applications in optical communications, security, sensing and imaging. Specific learning outcomes include:

1. Proficiency with Poisson shot noise process, interference and coherent optical detection
2. Being able to analyze novel optical receiver designs involving interferometers, photon detectors and electro-optic feedback
3. Develop appreciation of fundamental limits of the efficiency of encoding information in the photon.

Learning Outcomes:

Upon completion of this course students will be able to:

1. Understand and analyze (1) Poisson arrival process, which appear in optical detection, queueing theory, and other fields, (2) optical interference on linear optical circuits.
2. Analyze performance of novel optical receiver designs involving linear optical interferometers, photon detectors and electro-optic feedback, for applications to optical communications and sensing
3. Evaluate efficiency of encoding information in the photon, and the tradeoff between photon efficiency and spectral efficiency in optical communications.
4. [Graduate students only] Typeset project reports in LaTeX, an important skill to write professional research papers.

4. [Graduate students only] Gain confidence in giving talk on professional-level research to a scientific audience.
5. [Graduate students only] Independently tackle a research question and be able to deliver a formal technical presentation of their results.

Course objectives:

During this course students will:
1. Learn the fundamental limits of noise in optical detection
2. Learn how to translate noise in optical detection to limits of information encoding efficiency in the context of optical communication
3. Appreciate the role of pre-detection optical domain field manipulations for enhancing the performance of optical communications and sensing, and the need of a more powerful (quantum) theory of light to quantify the fundamental performance limits.

Absence and Class Participation Policy

The UA's policy concerning Class Attendance, Participation, and Administrative Drops is available at: http://catalog.arizona.edu/policy/class-attendance-participation-andadministrative-drop

The UA policy regarding absences for any sincerely held religious belief, observance or practice will be accommodated where reasonable, http://policy.arizona.edu/humanresources/religious- accommodation-policy.

Absences pre-approved by the UA Dean of Students (or Dean Designee) will be honored. See:

https://deanofstudents.arizona.edu/absences

Participating in the course and attending lectures and other course events are vital to the learning process. As such, attendance is required at all lectures and discussion section meetings. Students who miss class due to illness or emergency are required to bring documentation from their health-care provider or other relevant, professional third parties. Failure to submit third- party documentation will result in unexcused absences.

Course Communications

Online communications will take place via D2L and official UA email address.

Required Texts or Readings

No textbook required. Printed handouts, and recommended reading will be distributed and will also be posted on the course website/D2L.

Assignments and Examinations: Schedule/Due Dates

The course will consist of two lectures each week, each of duration 75 minutes, bi-weekly homework, and a semester-end presentation by students at the end of the course. Homework assignments will be distributed over D2L website. Homework assigned will be due by end of the day on the Friday of the subsequent week. Keeping deadline sharply is important – there will be 50% grading penalty between 0 – 72 hours after the submission deadline. Over 72 hours after deadline will see zero point in the grade. There will be one-time leniency forgiving for late submission.

Final Examination or Project

This course will not have a final examination. As a final project, students will select an advanced problem covered during the semester and provide a 15-minutre presentation of the chosen subject.

Grading Scale and Policies

Regular letter grades will be issued for the course. All homework and the end-of-semester presentation will be graded.

Homework	60
Class participation (attendance and Q&A)	20
Final presentation	20
Total	100

The assignment of a letter grade will be based on the cumulative percentage earned and awarded roughly based on the following:

90-100% = A, 80-89% = B, 70-79% = C, 60-69% = D, below 60% = E.

If the course is a 400/500:

Each homework assignment will contain advanced problems that will be marked mandatory for graduate students and will be incorporated into the overall score. All advanced problems will be optional for undergraduate students and will not count towards their homework score. For the final presentation at the end of the course, graduate students will be expected to give 15-minute individual presentations on one advanced problem of their choice. Undergraduate students will be allowed to form groups of up to 3 and give a 15 minute presentation on any one of the advanced problems assigned in the homework during the course.

Requests for incomplete (I) or withdrawal (W) must be made in accordance with the university policies, which are available at http://catalog.arizona.edu/policy/grades-andgrading- system#incomplete and http://catalog.arizona.edu/policy/grades-and-grading-system#Withdrawal respectively.

Scheduled Topics/Activities

Topics and a general calendar are below. There will be two 75-minute lectures each week and 2 hour-long office hour every week (1 hour with the instructor and 1 hour with the TA) for 14 weeks. During the 15th week, there will be 2 hours of student presentations. The course will consist of two lectures each week, each of duration 75 minutes, weekly homework, and a 15-minute presentation by students at the end of the course. Homework assignments will be distributed during the lectures, homework assigned each week (Tuesday and Thursday) will be due by end of the day on the Thursday of the subsequent week. Homework will be interspersed with "bonus problems" and "advanced" problem(s). The number of lectures stated against each topic below is a rough estimate.

1. Laser pulse and shot noise

    a. Introduction and course objectives
    b. The monochromatic laser light pulse
    c. Attenuation and phase: the phase-space picture of a laser pulse
    d. Ideal photon detection and the Poisson point process theory
    e. On-off keying optical communication

2. Interferometry and Kennedy-like optical receivers

    a. The two-port beam-splitter: destructive and constructive interference
    b. Binary state discrimination and the Kennedy receiver
    c. Phase-shift modulation
    d. Bondurant's receiver and Sequential wave form nulling
    e. Multi-port interferometers and role of feedback in optical receiver design

3. Minimum error binary and multi state discrimination: Dolinar's receiver and Helstrom Limit
    a. Analysis and discussion of Dolinar's feedback-based optical receiver for binary state discrimination
    b. Unambiguous discrimination versus minimum-error discrimination
    c. Calculation of fundamental limit of minimum probability of error for multiple state discrimination
    d. General discussion of quantum limits in optical detection
    e. Limitations of Dolinar-style receivers in multiple state discrimination, open questions

4. Coherent optical detection: Homodyne detection

    a. Detecting phase of the laser pulse: derivation of noise statistics of local-oscillator shot- noise-limited homodyne detection
    b. Binary phase modulation: comparing homodyne, heterodyne, Kennedy and Dolinar receivers
    c. Higher-order phase modulation: comparison of Bondurant and Heterodyne receivers. Error exponent analysis.

5. Information theory in optics

    a. The concept of a noisy communication "channel"
    b. Encoding messages in sequences of laser pulses: codewords
    c. Derivation of the Shannon capacity of a binary channel
    d. Super additivity in optical communication capacity via joint detection
    e. Examples of super additive receivers
    f. No go results in the design of super additive receivers using Dolinar-style feedback g. *Optional reading and assignment*–Holevo capacity of classical communication on a quantum (optical) channel

6. Optical communications

    a. The “pure-loss” optical channel
    b. Photon information efficiency versus spectral efficiency tradeoffs for various modulation formats and receiver designs

7. Optical sensing

    a. Sensing an unknown phase modulation
    b. The Mach-Zender interferometer (MZI)
    c. Sensing range and reflectivity of a single pixel; discussion of “first photon imaging”
    d. Discussion on standard quantum limit and the Heisenberg limit

10. End-of-semester student presentations

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.).

Students are asked to refrain from disruptive conversations with people sitting around them during lecture. Students observed engaging in disruptive activity will be asked to cease this behavior. Those who continue to disrupt the class will be asked to leave lecture or discussion and may be reported to the Dean of Students.

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.

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.

The University Libraries have some excellent tips for avoiding plagiarism, available at http://new.library.arizona.edu/research/citing/plagiarism.

Selling class notes and/or other course materials to other students or to a third party for resale is not permitted without the instructor's express written consent. Violations to this and other course rules are subject to the Code of Academic Integrity and may result in course sanctions. Additionally, students who use D2L or UA e-mail to sell or buy these copyrighted materials are subject to Code of Conduct Violations for misuse of student e-mail addresses. This conduct may also constitute copyright infringement.

UA Nondiscrimination and Anti-harassment Policy

The University is committed to creating and maintaining an environment free of discrimination; see http://policy.arizona.edu/human-resources/nondiscrimination-and-antiharassment-policy

Our classroom is a place where everyone is encouraged to express well-formed opinions and their reasons for those opinions. We also want to create a tolerant and open environment where such opinions can be expressed without resorting to bullying or discrimination of others.

Additional Resources for Students

UA Academic policies and procedures are available at http://catalog.arizona.edu/policies

Student Assistance and Advocacy information is available at

http://deanofstudents.arizona.edu/student-assistance/students/student-assistance

Confidentiality of Student Records

http://www.registrar.arizona.edu/personal-information/family-educational-rights-andprivacy- act-1974-ferpa?topic=ferpa

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.