THE UNIVERSITY OF ARIZONA

SYLLABUS

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

Spring 2019
Tuesdays/Thursdays: 12:30 – 1:45 PM
Meinel 305

Description of Course

This course will develop the mathematical theory of noise in optical detection from first principles, with the goal of understanding the fundamental limits of efficiency with which one can extract information encoded in light. We will explore how optical-domain interferometric manipulations of the information bearing light, i.e., prior to the actual detection, and the use of detection-induced electro-optic feedback during the detection process can alter the post-detection noise statistics in a favorable manner, thereby facilitating improved efficiency in information extraction. Throughout the course, we will evaluate applications of such novel optical detection methods in optical communications and sensing, and compare their performance with those with conventional ways of detecting light. We will also compare the performance of these novel detection methods to the best performance achievable---in the given problem context---as governed by the laws of (quantum) physics, without showing explicit derivations of those fundamental quantum limits. The primary goal behind this course is to equip students (as well as interested postdocs and faculty) coming from a broad background who are considering taking on theoretical or experimental research in quantum enhanced photonic information processing, with intuitions on a deeper way to think of optical detection, and to develop an appreciation of: (1) the value of a full quantum treatment of light to find fundamental limits of encoding information in the photon, and (2) how pre-detection manipulation of the information-bearing light can help dispose it information favorably with respect to the inevitable detection noise.

This course will not assume any background in optics, stochastic processes, quantum mechanics, information theory or estimation theory. However, an undergraduate mathematical background and proficiency in complex numbers, probability theory, and linear algebra (vectors and matrices) will be 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: Saikat Guha

Office: Meinel 523

Email: saikat@optics.arizona.edu

Phone: (520)621-7595

Office hours: 1 hour every week and by appointment

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.
5. [Graduate students only] Gain confidence in giving talk on original 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-and-administrative-drop

The UA policy regarding absences for any sincerely held religious belief, observance or practice will be accommodated where reasonable, http://policy.arizona.edu/human-resources/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 text book 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, weekly homeworks with around 6 problems, and a 15-minute presentation by students at the end of the course. Homework assignments will be distributed at the end of each lecture, and they will be due by noon on the day prior to the subsequent lecture. Homeworks will be interspersed with "advanced" problem(s). These advanced problems will not be due in class the following week. Each student (or groups of up to 3 students in case of undergraduate students) will choose any one of those advanced problems and present their solution at their end-of-term 15-minute presentation.

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 course of 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 homeworks and the end-of-semester presentation will be graded.

Homework (10 assignments total)	70%
Presentation	30%
Total	100%

The assignment of a letter grade will be based on the cumulative percentage earned and awarded 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 homeworks during the course. The 70-30 split of homeworks and presentation in the final grade, will be identical for graduate and undergraduate students.

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

Scheduled Topics/Activities

Topics and a general calendar are below. Homework assignments will be distributed at the end of each lecture, and they will be due by noon on the day prior to the subsequent lecture. There will be two 75-minute lectures each week and 1 hour-long office hour every week for 14 weeks. During the 15th week, there will be 2 hours of student presentations. The number of lectures stated against each topic below is a rough estimate.

1. Laser pulse and shot noise **[2 lectures]**
    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
    f. *Optional reading and assignment* – Discriminating pulse amplitude modulation (PAM)
2. Pulsed laser ranging **[2 lectures]**
    a. Mean squared error (MSE) analysis of single-pixel ranging
    b. Effects of pulse shape and rollover on ranging performance
    c. *Optional reading and assignment* – Cramer Rao bound on MSE
3. Interferometry and Kennedy-like optical receivers **[4 lectures]**
    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 waveform nulling
    e. Multi-port interferometers and role of feedback in optical receiver design
    f. *Optional reading and assignment* – General multiport interferometer design, conditional nulling receiver, generalized Kennedy receiver
4. Minimum error binary state discrimination: Dolinar's receiver **[4 lectures]**
    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
    f. *Optional reading and assignment* – Spatial versus temporal processing in feedback based receiver design, slicing receiver, incremental optimization during receiver operation versus global optimization
5. Coherent optical detection: Homodyne and Heterodyne detection **[3 lectures]**
    a. Detecting phase of the laser pulse: derivation of noise statistics of local-oscillator shot-noise-limited homodyne and heterodyne 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.
    d. *Optional reading and assignment* – Derivation of quantum limit of discriminating quaternary phase modulation and appreciation of the fact that no structured optical receiver design is known that achieves this optimal performance. The Green machine

receiver for binary modulated Hadamard codewords and its implications to deep space communications.

6. Information theory in optics **[2 lectures]**
    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. Superadditivity in optical communication capacity via joint detection
    e. Examples of superadditive receivers
    f. No go results in the design of superadditive receivers using Dolinar-style feedback
    g. *Optional reading and assignment* – Holevo capacity of classical communication on a quantum (optical) channel
7. Optical communications **[5 lecture]**
    a. The "pure loss" optical channel
    b. Photon information efficiency versus spectral efficiency tradeoffs for various modulation formats and receiver designs
    c. *Optional reading and assignment* – Capacity and finite-length performance of the sequential-nulling (Bondurant's) receiver. Capacity of direct detection, performance of most general coherent-detection receiver
8. Optical sensing **[5 lectures]**
    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
    e. *Optional reading and assignment* – LIGO, Adaptive homodyne measurement of optical phase, squeezed-light injection
9. Glimpses of advanced topics in quantum-enhanced photonic information processing **[1 lecture]**
    a. Optical imaging: multimode treatment of light- receivers to beat the Rayleigh resolution limit;
    b. Optical communications: Holevo capacity and codes, quantum-secured communications and key distribution, covert communications;
    c. Optical sensing: N00N state and squeezed-state interferometry, entanglement-assisted sensing (quantum illumination) for target detection and discrimination
    d. Optical quantum computing
10. End-of-semester student presentations **[2 hours]**

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-anti-harassment-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-and-privacy-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.