ENGN/PHYS 1790/2790 – Quantum Optics (Spring 2024)

Instructor: Prof. Domenico Pacifici (Domenico_Pacifici@brown.edu, B&H249, x3-2637)

COURSE DESCRIPTION

An introduction to the fundamental theory, mathematical formalism, and applications of quantum optics, the study of light and its interactions with matter at microscopic scales. Topics will include: an introduction to quantum mechanics using the bra-ket (or Dirac) notation, quantization of the electromagnetic fields, generation and detection of single photons, non-classical quantum states (single-mode states, Fock or number states, coherent and squeezed states), phasor diagrams, number-phase uncertainty, quantum theory of photoionization/photodetection, quantum description of mirrors, beam splitters, Mach-Zehnder interferometers, spontaneous emission and parametric downconversion, as well as interaction-free measurements. The course is intended for graduate and senior undergraduate students who would like to understand more advanced concepts in emerging fields, such as quantum computing. The material is self-contained, therefore students who do not have a deep background in quantum mechanics or optics will also be able to take the course proficiently.

PREREQUISITES

None. The course is self-contained.

COURSE GOALS

To help students develop a fundamental understanding of light-matter interactions and their applications in quantum optoelectronic devices and quantum computing.

COURSE FORMAT

Lecture, M 3:00-5:30pm (tentatively). Hands-on activities, in-class discussions, homework assignments, midterm and final examinations will foster the development of analytical skills and promote a deeper understanding of the language of quantum mechanics as it applies to quantum optics and quantum computing.

TOPICS

- Introduction/review of electricity & magnetism, Maxwell equations
- Complex representation of electromagnetic waves: plane waves, energy/intensity
- Introduction/review of quantum mechanics: matrix formulation, Hermitian operators, bra-ket (Dirac) notation, measurements, expectation values, uncertainty, commutator, symmetries, generators, time-evolution
- Quantization of the electromagnetic field
- Single-mode, Fock (or number), coherent, and squeezed states of light
- Electric field operator and quadratures
- Quantum entanglement, Qubits
- Coherence/Decoherence
- Phasor diagrams, number-phase uncertainty
- Quantum description of spontaneous emission and parametric downconversion
- Quantum theory of photoionization/photodetection
- Quantum description of mirrors, beam splitters, interferometers (Mach-Zehnder)
- Interaction-free measurements
- Single photon devices
- Examples and applications relevant to quantum computing

OFFICE HOURS

Prof. Pacifici: TBD at first meeting; both in-person and via zoom; also, by appointment.

REFERENCE TEXTBOOKS

"Getting Started in Quantum Optics" by Ray LaPierre, Springer (2022).
“Quantum Optics: An Introduction” by Mark Fox, Oxford University Press (2006).
“The Quantum Theory of Light” by R. Loudon, Oxford University Press (2010).
“Quantum Optics and Quantum Computation: An introduction” by D. Bhattacharyya and J. Guha, IOP Publishing (2022).
“Quantum Electronics” by A. Yariv, John Wiley and Sons, Inc., NY (1989).
“Photonics: Optical Electronics in Modern Communications” by A. Yariv and P. Yeh, Oxford University Press, 6th ed. (2007).
“Waves and Fields in Optoelectronics” by H.A. Haus, Prentice-Hall, Inc. (1984).
“Modern Quantum Mechanics” by J.J. Sakurai and J. Napolitano, Cambridge University Press (2020).
“Quantum Mechanics” by C. Cohen-Tannoudji, Bernard Diu, Frank Laloe, Vol. I and II, Wiley (1991).

LECTURE NOTES

Comprehensive lecture notes will be made available on Canvas prior to each class meeting. Students are encouraged to study the material beforehand and come prepared to class for an improved and more effective learning experience.

COURSE MATERIALS AND COST

No costs. Electronic copies of at least two of the recommended reference textbooks are available through Brown University’s Library services.

TENTATIVE GRADING

Homework assignments	~ 50%
Midterm examinations	~ 30%
Final exam	~ 20%

WORKLOAD EXPECTATION

Over the 14 weeks of this course, students will spend two and a half hours in class each week (35 hours total). Preparatory reading is estimated at 6 hours per week (84 hours total). Each of the five homework assignments will require approximately 7 hours to complete (35 hours total). Two midterms will require about 8 hours of preparation each (16 hours total). In addition, there will be a final examination for which at least 10 hours of work (including material review) is expected. Therefore, the total approximate time commitment is 180 hours.

COLLABORATION POLICY

Discussion among students is encouraged but all graded submissions must reflect and be the results of independent work.

ACCESSIBILITY AND ACCOMMODATIONS

Brown University is committed to full inclusion of all students. Please inform me early in the term if you may require accommodations or modification of any of course procedures. You may speak with me after class, during office hours, or by appointment. If you need accommodations around online learning or in classroom accommodations, please be sure to reach out to Student Accessibility Services (SAS) for their assistance (sas@brown.edu, 401-863-9588).

Undergraduates in need of short-term academic advice or support can contact an academic dean in the College by emailing college@brown.edu. Graduate students may contact one of the deans in the Graduate School by emailing graduate_school@brown.edu.

ACADEMIC HONESTY

Please review the Academic Code. All work submitted for grading should reflect your own individual work. Discussions with other students or the instructor are allowed, but copying is not acceptable. Violations of the Academic Code will lead to strict disciplinary action as outlined in the Code. Misunderstanding of the Code will not be accepted as an excuse for dishonest work.

Wk	Main Topics (tentative)	Dates and Sub-topics	Activity
1	Electricity and Magnetism	01/29 Introduction, review of Maxwell equations, complex notation, plane waves, electromagnetic (e.m.) energy/intensity	
2	Quantum Mechanics	02/05 Review of QM (I): matrix formulation, Hermitian operators, bra-kets (or Dirac) notation	**HW 1**
3		02/12 Review of QM (II): measurements, expectation values, uncertainty, commutator	
4		02/19 Review of QM (III): symmetries, generators, time-evolution	**HW 2**
5	Harmonic oscillator	02/26 Harmonic oscillator, coherent states	
6	Quantization and non-classical states of light	03/04 Quantization of the electromagnetic field	**Midterm 1**
7		03/11 Single-mode, Fock (or number) states, electric field operator and quadratures	
8		03/18 Phasor diagrams, number-phase uncertainty	**HW 3**
9		03/23-31 **no classes – Spring recess**	
10		04/01 Squeezed states	**HW 4**
11	Quantum description of light/matter interaction	04/08 Quantum picture of spontaneous emission and parametric downconversion	
12		04/15 Quantum theory of photoionization/photodetection	**Midterm 2**
13		04/22 Quantum description of mirror, beam splitter, Hong-Ou-Mandel (HOM) dip	
14		04/29 Mach-Zehnder interferometer, interaction-free measurements, examples	**HW 5**
15	Additional examples, applications to quantum computing, and final review	05/06 Additional examples, quantum computing, final review 05/07 Classes end for courses not observing the Reading Period 5/08-17 **Final Examination Period**	**Final Exam**

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N.B.: Lecture notes, slides, and additional reading materials will be provided.