ECE 770 - Topics 21: Modern Quantum Optics and Nanophotonics

(Fall 2025)

Course Description:

This course will introduce a selection of topics in quantum optics and nanophotonics with a focus toward potential applications to provide foundations for contemporary research. Areas covered will include basic concepts and theoretical tools of light matter interaction, including semi-classical and quantized model; non-classical light; localization of light and applications: photonic crystals, optical waveguides, microresonators, plasmonics, and metasurfaces; fundamentals of cavity quantum electrodynamics: strong and weak-coupling regime, Purcell factor, spontaneous emission control; electromagnetically induced transparency: slow light, photon storage, single-photon switching.

Prerequisites:
Advanced undergraduate or basic graduate level knowledge of electromagnetism and quantum mechanics. Prerequisites can be waived with instructor's permission.

Contact Information:

Instructor: Prof. Michal Bajcsy

Office: QNC 4126, Schedule meeting by appointment or ask a question via MS Teams

Email: mbajcsy@uwaterloo.ca

Teaching Assistants: TBA

Lectures:

Location: EIT 3141

Schedule: Tuesday and Thursday, 2:30-3:50pm

Course Topics:

1. Semiclassical model of light-matter interactions:
   • review of quantum mechanics: states, time evolution, density matrix
   • two-level atoms interacting with classical fields: Rabi flopping, Bloch sphere and Bloch equations, effects of spontaneous emission
   • weak probe approximation and slowly-varying envelope approximation
   • three-level atoms interacting with classical fields: electromagnetically induced transparency and slow light

2. Introduction to optical resonators
   • losses, Q-factor, finesse, free spectral range, mode volume of a resonator

3. Mechanisms for confinement and steering of light
   • total internal reflection (TIR)
   • electromagnetic propagation in periodic media: Bloch waves and band structure, photonic crystals

4. Optical microcavities
   • TIR-based resonators
   • resonators based on photonic crystals
   • plasmonic cavities

5. Electromagnetic field quantization
   • lossless 1D resonator with a uniform dielectric field constant
   • free space
   • lossy resonator: quantum Langevin equation

6. Cavity quantum electrodynamics with single atoms
   • strong coupling regime
   • weak coupling regime
   • density of photon states and spontaneous emission rate
   • Lindblad superoperator and quantum master equation
   • quantum emitters in contemporary research

7. Quantum optics with atomic ensembles
   • collective states and dark state polaritons
   • photon storage
   • Rydberg blockade and 'light-sabers'

8. Introduction to atom cooling and trapping
   • laser cooling, magnetic traps, optical dipole traps

9. Single-photon sources and detectors

Assessment:

- *Homeworks* (5 sets): 30%
- *Term paper* (5-10 pages) with class presentation (10-15min): 20%
- *Final exam* (48 hour take-home consisting of writing a referee report for an assigned journal article): 50%
- 20% assignments, 10% midterm test, 20% project, 50% FINAL EXAM
- **Graded Assignment Collection**: Assignments must be submitted online via Crowdmark by the due date, otherwise a grade of 0% for that assignment will be given. Graded assignments will be available approximately two weeks after

they are due

- **Assignment Solutions:** Solutions will be available on LEARN after the due date

  Please Note: *No late assignments will be accepted for credit without prior consultation with the course instructor*

Tentative Course Schedule:

Topic	Tentative Dates
Semiclassical model of light-matter interactions	September 4, 9, 11, 16
Assignment 1	**Issued September 9, due September 23**
Introduction to optical resonators	September 18
Assignment 2	**Issued September 23, due October 7**
Mechanisms for confinement and steering of light	September 23, 25, 30, October 2
Optical microcavities	October 7, 9
Reading week – October 11 to 19	
Electromagnetic field quantization	October 21, 23
Assignment 3	**Issued October 21, due November 4**
Cavity quantum electrodynamics with single atoms	October 28, 30, November 4, 6
Assignment 4	**Issued November 4, due November 18**
Term paper proposal	**Due November 11**
Quantum optics with atomic ensembles	November 11, 13
Assignment 5	**Issued November 11, due November 25**
Introduction to atom cooling and trapping	November 18, 20
Single-photon sources and detectors	November 25, 27
Project presentations	December 2

Additional information:

Academic integrity: To maintain a culture of academic integrity, members of the University of Waterloo community are expected to promote honesty, trust, fairness, respect, and responsibility. [Check the Office of Academic Integrity for more information.]

Grievance: A student who believes that a decision affecting some aspect of his/her university life has been unfair or unreasonable may have grounds for initiating a grievance. Read Policy

70, Student Petitions and Grievances, Section 4. When in doubt, please be certain to contact the department's administrative assistant who will provide further assistance.

Discipline: A student is expected to know what constitutes academic integrity to avoid committing an academic offence, and to take responsibility for his/her actions. [Check the Office of Academic Integrity for more information.] A student who is unsure whether an action constitutes an offence, or who needs help in learning how to avoid offences (e.g., plagiarism, cheating) or about "rules" for group work/collaboration should seek guidance from the course instructor, academic advisor, or the undergraduate associate dean. For information on categories of offences and types of penalties, students should refer to Policy 71, Student Discipline. For typical penalties, check Guidelines for the Assessment of Penalties.

Appeals: A decision made or penalty imposed under Policy 70, Student Petitions and Grievances (other than a petition) or Policy 71, Student Discipline may be appealed if there is a ground. A student who believes he/she has a ground for an appeal should refer to Policy 72, Student Appeals.

Note for students with disabilities: AccessAbility Services, located in Needles Hall, Room 1401, collaborates with all academic departments to arrange appropriate accommodations for students with disabilities without compromising the academic integrity of the curriculum. If you require academic accommodations to lessen the impact of your disability, please register with AccessAbility Services at the beginning of each academic term.

Turnitin.com: Text matching software (Turnitin®) may be used to screen assignments in this course. Turnitin® is used to verify that all materials and sources in assignments are documented. Students' submissions are stored on a U.S. server, therefore students must be given an alternative (e.g., scaffolded assignment or annotated bibliography), if they are concerned about their privacy and/or security. Students will be given due notice, in the first week of the term and/or at the time assignment details are provided, about arrangements and alternatives for the use of Turnitin in this course.

It is the responsibility of the student to notify the instructor if they, in the first week of term or at the time assignment details are provided, wish to submit alternate assignment.

Use of GenAI in Course ECE 770. Generative artificial intelligence (GenAI) trained using large language models (LLM) or other methods to produce text, images, music, or code, like Chat GPT, DALL-E, or GitHub CoPilot, may be used for assignments in this class with proper documentation, citation, and acknowledgement. Recommendations for how to cite GenAI in student work at the University of Waterloo may be found through the Library: https://subjectguides.uwaterloo.ca/chatgpt_generative_ai.

Please be aware that generative AI is known to falsify references to other work and may fabricate facts and inaccurately express ideas. GenAI generates content based on the input of other human authors and may therefore contain inaccuracies or reflect biases. In addition, you

should be aware that the legal/copyright status of generative AI inputs and outputs is unclear. Exercise caution when using large portions of content from AI sources, especially images. More information is available from the Copyright Advisory Committee: https://uwaterloo.ca/copyright-at-waterloo/teaching/generative-artificial-intelligence. You are accountable for the content and accuracy of all work you submit in this class, including any supported by GenAI.