Modern Quantum Optics and Nanophotonics

Proposed as new addition to the ECE/QIC Curriculum, Electrical and Computer
Engineering Department, University of Waterloo, Ontario, Canada

ECExxx
Fall 2014
Meeting Time: Monday 11:30am-2:20pm
Room: EIT-3141

Instructor: Prof. Michal Bajcsy
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1. Background

Physical systems in which nonlinear light-matter and light-light interactions at few photon levels can be achieved and controlled has been a long-standing focus of both science and engineering. The motivations for these efforts range from highly applied, such as development of devices for high-speed and low-power processing or transfer of information and high-precision metrology, to more fundamental such as studies of quantum- mechanical phenomena in condensed matter or atomic systems and proposals for scalable quantum computers.
Quantum emitters – such as quantum dots, diamond nitrogen-vacancy centers, or laser-cooled atoms – coupled to optical resonators or photonic waveguides are currently being explored as future platforms for controllable implementation of light-matter and light-light interactions at single or few photon level. Nano-scale photonic structures are now able to implement these systems and many more by taking advantage of micro- and nano-fabrication technologies. These structures can steer the flow of photons on length-scales comparable to the wavelength of light with a degree of control over the photonic environment that was until recently impossible. Proof-of-principle systems based on single quantum emitters as well as ensembles of emitters coupled to individual nano-photonic structures have been reported extensively over the last few years and the field of developing these systems into practical devices that can be cascaded or scaled into large architectures is rich with great potential rewards, challenging research problems.

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 in experimental implementation of scalable quantum information processing platforms based on non-linear light-matter interactions.

Primarily for graduate students; advanced undergraduates eligible with instructor's permission.

2. Catalogue 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; 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.

3. Syllabus

13 Lectures. One three-hour lecture per week (with 30 min break).
Total Instruction: 35 Hours

Week 1 & 2: Introduction to optical resonators

- losses, Q-factor, finesse, free spectral range, mode volume of a resonator

Mechanisms for confinement of light

- total internal reflection (TIR)
- electromagnetic propagation in periodic media: Bloch waves and band structure
- photonic crystals, photonic bandgap
- surface plasmons

Week 3 & 4: 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

Week 5: Electromagnetic field quantization

- lossless 1D resonator with a uniform dielectric field constant
- free space
- lossy resonator: quantum Langevin equation

Week 6 & 7: Introduction to cavity quantum electrodynamics

- 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

Week 8: Types of optical microcavities

- TIR-based resonators
- resonators based on photonic crystals
- plasmonic cavities

Week 9: Introduction to atom cooling and trapping

- laser cooling, magnetic traps, optical dipole traps
- evaporative cooling and Raman sideband cooling

Week 10: Non-classical states of light

- single-photon sources
- entanglement
- single-photon detectors
- HBT and HOM measurements

Week 11: Dark state polaritons

- photon storage
- Rydberg blockade and 'light-sabers'

Week12: All-optical switching at fundamental limits

- single-photon switching demonstrations
- optical transistors

Week 13: Term paper presentations

4. Term paper and Presentation

Students will write a 3-5 page term paper on a topic of their choice related to the material covered during the course and deliver a 15-20 min oral presentation of their paper in front of the class followed by a 5 min Q&A discussion.

5. Course Material

Class notes and hand-outs; assigned journal papers.

6. Grading

Homeworks: 30%; Term paper and Presentation: 20%; Final exam: 50%

7. Prerequisites

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