OPTI 560- Quantum Nanophotonics Syllabus

Mohamed ElKabbash

Spring 2025

Quantum Nanophotonics deals with quantum emitters and quantum light sources. Our goal is to use nanophotonic devices to engineer light-matter interaction with these emitters. This is a rich and diverse field. The course is designed to make you sufficiently fluent in Quantum Nanophotonics to be able to understand a *well written* scientific paper in the field by only reading the abstract and the paper's figures.

Here, I detail all the lectures that hopefully we manage to squeeze in one semester and the homework that will be assigned to you. All the grades are based on the homework (80%) + a final exam (20%). The final exam is one-to-one exam where you will be asked to read a paper based on its abstract and figures and answer my questions on the work. Each homework is 10% of your grade. You will be given the top 8 grades of all your homework assignments.

Lecture 1: Introduction to Quantum Nanophotonics

1. Nanophotonics

Nanophotonics is the study and application of light-matter interactions on the nanoscale. This field includes:

- **Photonic Crystals:** Photonic bandgap engineering.
- **Metamaterials:** Optical dispersion engineering.
- **Plasmonics:** Near field engineering.
- **Metasurfaces:** Optical mode engineering.
- **Photonic Integrated Circuits (PICs):** Putting it all together to make a circuit.

2. An introduction to Quantum Photonics

Quantum photonics explores the quantum properties of light and its applications in quantum technologies, including:

- **Quantum Communication:** Using photons as information carriers for secure communication, such as quantum key distribution (QKD).
- **Quantum Computing:** Leveraging photons as *robust* qubits to perform quantum computations using linear optics and quantum gates.
- **Quantum Sensing:** Exploiting quantum states of light, such as squeezed states, quantized energy levels, entanglement, and photon correlations, for precision measurements beyond classical limits.
- **Quantum Imaging:** Enhancing imaging techniques with quantum correlations and entangled photons for better resolution and sensitivity.

3. Quantum Nanophotonics goals

Enhancing light-matter interactions at the nanoscale to generate, manipulate, propagate, and detect quantum light.

4. Lecture 1 HW

You will learn how to make mind maps. Your homework is to make a mind map for one topic in nanophotonics and another in quantum photonics. Then, you will make a mind map connecting both topics you picked. The best mind map in each category will be used as an example for next year's class.

Lecture 2: Refraction and Reflection

1. Refraction

- Physical origin of refraction
- Effective medium approximation and Metamaterials
- Time refraction

2. Reflection

- Physical origin of reflection in metals
- Physical origin of reflection in dielectrics
- Dielectric Bragg mirrors
- Diffractive mirrors
- Time reflection

3. Lecture 2 HW

Make a mind map for both topics discussed in the lecture.

Lecture 3: Waveguides and Cavities

1. Waveguides

- Concept of waveguiding
- Dielectric waveguides
- Photonic crystal waveguides
- Surface plasmon polaritons and surface phonon polaritons

2. Cavities

- Concept of cavities
- Types of cavities:
  - Mirrors
  - Ring resonators
  - Photonic crystal cavities
  - Whispering gallery modes
  - Plasmonic nanocavities
- Quality factor, Finesse, and Modal Volume

3. Lecture 3 HW

Pick three subtopics, then review 3 published papers that discuss the design of one of these devices. You will act as a peer reviewer. First provide a detailed summary of the work. Then point out issues in the presentation, technical aspects, and claims of these works.

Lecture 4: Concept of Modes

You will hear the word modes all the time. Modes are eigenstates, so how they look depends on the particular system. This lecture will discuss the modes you will deal with most of the time and importantly how modes interact with each other. Coupling modes together is at the core of quantum nanophotonics.

1. Modes in Mechanical Springs

2. Modes in Waveguides

3. Modes in Cavities

4. Modes in Free Space

5. Coupled Mode Theory

- Basics of coupled mode theory
- Applications in photonics (waveguides and cavities)

6. Green's Function for Energy Transfer

- Introduction to Green's function
- Energy transfer processes using Green's function

7. Lecture 4 HW

Write a code that models a directional coupler based on coupled mode theory.

Lecture 5: Quantum Emitters

1. Types of Quantum Emitters

- Color centers
- Excitons in 2D materials
- Quantum dots
- Atoms

2. Single Photon Source Metrics

- Brightness and origins of low brightness
- Coherence and origins of decoherence
- Dephasing
- Purity
- Indistinguishability

3. Lecture 5 HW

Pick a scientific paper that discusses improvement on one of the single photon source metrics using nanophotonics. Provide a peer review to that paper. Design an experiment using an alternative nanophotonic system that would also improve the same metric and contrast the two systems.

Lecture 6: Modified Spontaneous Emission Process

1. Key Concepts

- Purcell effect
- Local density of optical states
- Enhanced and suppressed spontaneous emission rate

2. Implementations of Modified Spontaneous Emission Rate

- Drexhage effect and dipole-image dipole interaction
- Waveguide quantum electrodynamics (QED)
- Cavity quantum electrodynamics (QED)
- Plasmonic cavity QED (low modal volume systems)
- Bound state in the continuum High-Q modes

3. Lecture 6 HW

Model the purcell enhancement of a quantum emitter in a plasmonic nanocavity using finite difference time domain method. We will provide you a template for the code. You will explore varying parameters and write a scientific paper that discusses how these parameters affect the spontaneous emission rate of the emitter.

Lecture 7: Nonlinear Quantum Light Sources

1. Introduction to Nonlinear Quantum Light Generation

2.Nanophotonic Architectures for Nonlinear Quantum Light Sources

3. Lecture 7 HW

PsiQuantum and Xanadu are two major players in the Quantum Nanophotonics industry. Write a progress report on their use of nonlinear quantum light source generation.

Lecture 8: Experiments on Quantum Light Sources

1. Experimental Metrics

- Brightness
- Coherence
- Purity
- Indistinguishability

2. Lecture 8 HW

Use Inkscape and the open source gwoptics component library to draw the experimental setups used to determine each figure of merit for quantum light sources. Caption these figures to explain in details what each component in your setup does.

Lecture 9: Strong Coupling Regime

1. Strong vs Weak Coupling

- Differences between strong and weak coupling regimes

2. Strong Coupling Implementations

- Emitters and dielectric cavities
- Emitters and plasmonic cavities
- Quantum photonic applications of strong coupling

Lecture 10: Single Photon Detectors

1. Overview of Single Photon Detection

- Principles of single photon detection

2. Nanophotonic Devices for Single Photon Detection

- Implementation of nanophotonic detectors

3. Lecture 10 HW

The entire class will invent a new method to detect single photons using nanophotonic concepts we learned so far. We will first survey the literature to find out existing nanophotonic-based techniques for single photon detection. Then, we will categorize them and provide key performance metrics. We will explore which challenges remain unsolved. Then students will contribute ideas to overcome these challenges. If a patent comes out of this, students who provided an intellectual contribution (judged by myself) will be on the patent with a share corresponding to their contribution in the conception, design, and modeling of the device.

Lecture 11: Quantum Photonic Systems - Quantum Computing

1. Key Processes in Quantum Computing

- Generation of quantum light
- Control of quantum light
- Detection of quantum light

2. Lecture 11 HW

Provide a progress report on Quantum nano-photonic systems for quantum computing. Again we will focus on PsiQuantum and Xanadu.

Lecture 12: Quantum Sensing

1. Main Concepts in Quantum Sensing

- Fundamentals of quantum sensing

2. Implementation in Nanophotonic Devices

- Nanophotonic platforms for quantum sensing

3. Lecture 12 HW

This is an open question. How can we use quantum sensing to improve the performance of inertial measurement units in drones. Provide a detailed analysis on whatever idea you can come up with.

Lecture 13: Quantum Communication

1. Quantum Key Distribution (QKD) Techniques

- Entanglement-based QKD
- Single photon-based QKD
- Squeezed state QKD

2. Nanophotonic Implementations

3. Lecture 13 HW

Write a summary of the state-of-the-art systems in QKD, compare their metrics and potential applications for each type.

Lecture 14: Cooperative Effects and Time-Varying Q Nanophotonics

1. Superradiance

- Concepts and fundamentals of superradiance
- Implementation in nanophotonic platforms

2. Quantum Mirrors and Q Metasurfaces

- Role of quantum mirrors
- Q metasurfaces for photonic applications

3. Time-Varying Quantum Light Generation

- Techniques for time-varying quantum light generation
- Applications in quantum photonics

Final Exam

You need to take a license from the class instructor that you are an expert in quantum nanophotonics. This will only happen if you successfuly pass this oral 1-1 exam.