FCC185 From quantum optics to quantum technologies, 7.5 credits

Från kvantoptik till kvantteknologier, 7,5 högskolepoäng

Second Cycle

Confirmation

This course syllabus was confirmed by Department of Physics on 2024-01-31 to be valid from 2024-09-02, autumn semester of 2024.

Field of education: Science 100%
Department: Department of Physics

Position in the educational system

elective course

The course can be part of the following programmes: 1) Complex Adaptive Systems, Master's Programme (N2CAS) and 2) Physics, Master's Programme (N2PHY)

Main field of studies	*Specialization*
Physics	A1N, Second cycle, has only first-cycle course/s as entry requirements

Entry requirements

A Bachelor's degree in Physics, or equivalent, including course in quantum mechanics.

Applicants must prove their knowledge of English: English 6/English B from Swedish Upper Secondary School or the equivalent level of an internationally recognized test, for example TOEFL, IELTS.

Learning outcomes

The course introduces how one can describe, manipulate, and detect quantum mechanical systems such as single atoms and photons, and how advances in the control and measurement of these systems are driving the so-called “second quantum revolution” through the four pillars of quantum technologies: quantum computation, quantum simulation, quantum communication, and quantum sensing. This revolution is being pushed forward by large research initiatives worldwide, such as the Wallenberg Centre for Quantum Technology (WACQT) in Sweden, of which Chalmers is the main node, the EU Quantum Flagship in Europe, and many more. The course gives an overview on this very active field of research and connects – via lectures, exercise sessions, and a laboratory session in a state-of-the-art facility – to ongoing research on quantum mechanical superconducting circuits, microwave photons, and optomechanical systems.

After the course the student should be able to:
- Understand the difference between classical and non-classical radiation
- Explain the properties of the Jaynes-Cummings model
- Use the Bloch equations to describe the dissipative dynamics of a quantum mechanical two-level system
- Compute the output state of simple quantum circuits composed of elementary single-qubit operations, entangling gates and measurements
- Have a basic knowledge of the leading architectures to build a quantum computer and their comparative advantages and disadvantages
- Understand the difference between a quantum computer and a quantum simulator, and discuss use cases for both
- Understand how quantum technology may threaten today’s encryption keys and how secure communication can be established by quantum links
- Explain the standard quantum limit and how to break it
- Explain and experimentally perform manipulations and tomographic measurements of quantum states of a microwave resonator, assisted by a superconducting qubit

Course content

In the first part of the course, we will study the foundations of quantum optics, that is, how matter (atoms) interacts with an electromagnetic field at the quantum level (photons). We will study both the semi-classical and the full quantum light-matter interaction and get to know different quantum states of light and their quantum optical description. In experiments that implement these building blocks of quantum optics, one can use a diverse set of physical systems, for example, atoms, trapped ions or artificial atoms such as superconducting microelectronic circuits that possess quantum mechanical properties like atoms.

In the second part, we will apply the formalism of quantum optics to various physical platforms including superconducting circuits, trapped ions, cold atoms, nitrogenvacancy centers in diamond and mechanical resonators . Here the goal is to understand how quantum effects can be exploited to build novel devices and to use novel measurement techniques, that are key for all four pillars of quantum technology. Quantum computers allow to perform certain computations or simulations by using quantum algorithms that are faster than the corresponding classical algorithms. The development of quantum simulators can be traced back to R. Feynman's intuition that carefully engineered quantum systems could be used to efficiently simulate materials and molecules, potentially leading to breakthroughs in material science and chemistry. Quantum communication systems allow performing quantum key distribution over absolute safe channels and can connect quantum computers over large distances. Finally, quantum sensors take advantage of quantum phenomena such as state superposition and squeezing to build sensors, imaging systems, and metrological standards with unprecedented accuracy.

Part I

1. Building blocks of quantum mechanics and quantum optics
2. Photons: classical and non-classical states of radiation
3. Wigner functions and Wigner tomography
4. Atom-field interactions: Rabi oscillations and the Jaynes-Cummings Hamiltonian
5. Quantum decoherence and the Bloch equations
6. Readout of quantum information

Part II

1. Basics of quantum information processing
2. Overview of architectures for quantum information processing
3. Circuit quantum electrodynamics and its applications
4. Quantum simulation
5. Quantum communication
6. Microwave-to-optical transduction
7. Quantum sensing

Form of teaching

Lectures, exercises, home work, and a state-of-the art experiment with report writing

Language of instruction: English

Assessment

The course examination will consist of: 4 obligatory hand-ins, lab report and exam. To pass the course, you need to obtain at least 40% of the points on the exam and participate in the lab and submit a written lab report. The grade will then be based on: exam (50%), hand-ins (35%) and lab report (15%).

If a student who has twice received a failing grade for the same examination component wishes to change examiner ahead of the next examination session, such a request should be made to the department in writing and should be approved by the department unless there are special reasons to the contrary (Chapter 6 Section 22 of the Higher Education Ordinance). If a student has received a recommendation from the University of Gothenburg for study support for students with disabilities, the examiner may, where it is compatible with the learning outcomes of the course and provided that no unreasonable resources are required, decide to allow the student to sit an adjusted exam or alternative form of assessment. In the event that a course has ceased or undergone major changes, students are to be guaranteed at least three examination sessions (including the ordinary examination session) over a period of at least one year, but no more than two years after the course has ceased/been changed. The same applies to internships and professional placements (VFU), although this is restricted to just one additional examination session.

Grades

The grading scale comprises: Pass with Distinction (VG), Pass (G) and Fail (U).

Course evaluation

The results of and possible changes to the course will be shared with students who participated in the evaluation and students who are starting the course.