Course Package

Optics – 1A + 1B

Name module	Optics - 1A + 1B
Educational programme	MSc Applied Physics
Period	First semester (block 1A+1B)
Study load	30 ECTS

Optics			
block 1A	**block 1B**	**block 2A**	**block 2B**
Electives: choose 15 EC	***Electives: choose 15 EC***		
Quantum Mechanics 2 **202200093** (5 EC	**Laser Physics and Nonlinear Optics** **202200295** (5 EC)		
Biophysical Techniques & Molecular Imag. **193640020** (5 EC)	**Advanced Quantum Mechanics** **193570050** (5 EC)		
Fundamentals of Photonics **202200044** (5 EC)	**Quantum Optics** **202100083** (5 EC)		
Quantum Information **202100078** (5 EC)	**Nano-Electronics** **193400141** (5 EC)		

Required preliminary knowledge: Completed Bachelor's (Applied) Physics and Basic Quantum; Quantum mechanics; A bachelor's degree in Applied Physics; Biomedical Technology or Advanced Nanotechnology; Hilbert Spaces, and Quantum Mechanics courses (i.e. introductory quantum mechanics and linear algebra); Bachelor Optics course (B2) and Master Wave Optics course (Q1) are strongly recommended; Quantum Mechanics 2; Nanoscience; Introduction to Solid State Physics and Electrodynamics.

Block 1A

Electives: choose 15 EC

202200093 - Quantum Mechanics 2

In this course, we ask the question: How can we apply the fundamental principles of quantum mechanics to systems beyond the hydrogen atom and to systems that interact with electromagnetic radiation? We start by recapping the structure of the solution of the hydrogen atom and define the ingredients that are needed to describe systems that consist of more than one electron and proton: coupling of angular momenta, symmetries, and particle-particle interactions. The latter are neglected in this course and will be introduced elsewhere. The former two and their intimate relationship with each other will be discussed in detail. This will then allow us to gain an approximate understanding of the periodic table of elements and even of the electronic structure of some molecules.

We will then use the concept of perturbation theory (time-independent and time-dependent) to understand effects like the fine structure of the hydrogen atom and how matter interacts with electromagnetic radiation, deriving Fermi's famous Golden Rule. Finally, we will look at scattering problems and approximate ways for solving them with many important applications in diverse areas such as X-rays and particle physics.

193640020 - Biophysical Techniques & Molecular Imaging

Luminscence: Fluorescence, phosphorescence, bioluminescence; advanced luminescence principles: polarization, lifetime; bulk and single molecule approaches; imaging and spectroscopy in a microscope; intrinsic and extrinsic fluorophores; protein fluorescence; genetically encodable fluorescent markers, nanoparticles

Microscopy: wide-field, dark field, confocal, phase contrast, fluorescence microscopy (FRAP, FLIP, FLIM, FRET), micro-spectroscopy, hyperspectral imaging, polarization contrast, lifetime imaging, resonance energy transfer imaging, nano-particle imaging, non-linear microscopy.

Vibrational Spectroscopy and Imaging: label-free contrast methods such as spontaneous Raman micro-spectroscopy, Infrared microscopy, CARS microscopy, non-linear fluorescence microscopy and single molecule micro-spectroscopy.

202200044 - Fundamentals of Photonics

The wave nature of electromagnetic radiation forms the basis of high-speed internet and wireless communications, which are an integral part of our society. In this course we build upon and extend the wave concept of light as introduced in the bachelor Optics course. We revisit the wave equation and introduce the concept of Green's functions. Also, we will consider light-matter interaction in various configurations. We discuss the Lorentz and Drude model to explain the origin of refractive index of materials, and what surface plasmon polaritrons are. We also investigate how particular distributions of the refractive index, modify light propagation. This includes photonic crystals, waveguiding and scattering of light. We discuss the use of the transfer matrix method to model light propagation through a stack of thin films. The students will be introduced to the concept of wavefront propagation and this concept is used to discuss the point spread function and resolution of an imaging system. We will also illustrate how wavefront propagation has been used to solve various optical problems encountered in industry. Finally, we discuss how the wavelength dependent refractive index will modify the propagation of a (short) light pulse by introducing the concept of chirp filters.

202100078 - Quantum Information

One of the most exciting developments in physics in the last decade has been the development of quantum computing systems of increasing size and complexity. The crowning achievement (for the moment) has been the construction and operation of the first quantum devices able to outperform a classical computer at a well-defined computational task. Such so-called 'quantum supremacy' is the first milestone in the worldwide drive to build universal, large-scale quantum computers.

This course will teach the fundamentals of quantum information theory necessary to understand these and other recent developments in the quantum world.

The course will consist of four parts:

In the first part, we will slightly 'upgrade' the mathematical and theoretical abstraction level at which we do quantum mechanics and linear algebra, taking as our starting point where we left off in the Hilbert Spaces course in the bachelor. We will treat operator exponents, the singular value decomposition, density matrices, Pauli operators and density matrices.

In the second part, we will use this new-found knowledge to discuss many of the famous basic concepts and experiments in quantum information theory, including entanglement, quantum teleportation, the Einstein-Podolski-

Rosen experiment, Bell tests, and so on. We will also briefly discuss open quantum systems and the representation of noise in quantum systems.

In the third part, we will bring some computer science in the mix. We will discuss quantum computers, including the Solovay-Kitaev theorem, quantum error correcting codes, the threshold theorem, Grover's and Shor's algorithm, the stabilizer formalism, the Gottesman-Knill theorem and quantum simulation.

Finally, we will focus on current developments in experimental quantum information processing. We will discuss the notion of a quantum advantage, NISQ, sampling problems, and the prospects for near-term applications of quantum systems. We will also discuss experimental progress on the various experimental computing platforms.

The course material will consist of the book "Quantum Computation and Quantum Information: 10th Anniversary Edition, Nielsen and Chuang". Note that there are different editions of this book, which have discrepancies in page numbering and assignment numbering between them. Please make sure you purchase the 10th anniversary edition as noted above.

Block 1B

Electives: choose 15 EC

202200295 - **Laser Physics and Nonlinear Optics**

This course aims to provide a basic understanding of lasers and nonlinear optics.

In the first part of the course, we focus on the fundamental concepts of lasers. We use the classical Lorentz oscillator to revisit the origin of absorption, emission, of the refractive index and discuss spectral line broadening and its consequences for laser oscillation. We describe how to use rate equations for occupancy of atomic levels and photons to describe optical gain, the laser threshold, gain saturation, spectral and spatial hole burning, and how to achieve mode selection. To explain the generation of light pulses with ultrashort duration (e.g., in the femtosecond range), we describe mode-locking of lasers. Finally, we discuss the difference between light generated by stimulated versus spontaneous emission.

In the second part of the course, we focus on nonlinear optical processes induced by intense laser light. We extend the classical Lorentz oscillator model to illustrate the origin of the nonlinear optical response of materials and introduce the nonlinear optical polarization. We introduce the coupled wave equations for second-order nonlinear processes to discuss the central concepts of phase matching and quasi-phase matching and discuss examples like second-harmonic and sum-frequency generation. Furthermore, we show how these parametric nonlinear optical processes can be distinguished from incoherent processes emitting at the same wavelength. We discuss the Manley-Rowe relations that can be derived from the coupled wave equation and the quantum picture of such nonlinear processes. As examples of third-order nonlinear processes, we discuss the Kerr effect and stimulated Brillouin scattering and how the latter can be applied to process light.

193570050 - **Advanced Quantum Mechanics**

This master course introduces some of the more advanced tools of quantum mechanics, such as representation theory, Green functions, second quantization and quantum fields. A prominent tool is time-dependent perturbation theory, which can be represented in a physically intuitive way by Feynman diagrams. Examples of applications are taken mainly from solid state physics (phonons, electron gas, superconductors) and from optics (photons). The course is intended for master students who take an interest in theoretical physics.

202100083 - Quantum Optics

In this course, we study the quantum properties of light and matter-light interaction, with some examples from modern quantum technologies, such as laser cooling and trapping, Bose-Einstein condensation and quantum sensing. After an introduction to the formalism of quantum optics, we dive into light-matter interaction. We start with the quantization of the electromagnetic field, which leads to the introduction of the photon as the quantum of light. Then, we look at various interesting quantum states of the light field and their statistical properties, including the seminal Hanbury-Brown Twiss and Hong-Ou-Mandel experiments. Next, we introduce the machinery of multi-particle quantum optics, which will be needed in the rest of the course.

In the second part, we take a look at light-matter interaction, treating the Bloch sphere, Cavity QED and the Jaynes Cummings model, with applications to atom clocks, and quantum memories.

Finally, we turn to laser cooling and trapping and Bose-Einstein condensation. Here, we encounter some of the groundbreaking experiments from the last 25 years, showing, e.g. quantum phase transitions and the condensation of gases (or light!) to a macroscopic quantum ground state.

193400141 - Nano-Electronics

Nanoelectronics comprises the study of the electronic and magnetic properties of systems with critical dimensions in the nanoregime. Quantum electronics, spin electronics, organic electronics and neuromorphic electronics form important subfields of nanoelectronics and are being discussed in this course. Quantum electronics and neuromorphic electronics will be treated in-depth. For those who want to get a thorough introduction into the new exciting directions that will contribute to future electronics, this course is indispensable. Recommended for MSc students Nanotechnology. Applied Physics and Electrical Engineering. The course consists of lectures, assessments and a project. In the project, a small research proposal is written on a theme related to the course. The proposal is presented in written and oral form and graded by the lecturers.

Please note: these packages are not fixed. They serve as an example of what you are able to select. It may be possible for you to make changes if you would like to do so.

The modules are tentative and subject to change. Please check the website *regularly.*