Module Descriptions

Master of Science Quantum Engineering

Examination Regulations in the Version of: 2023
<table>
<thead>
<tr>
<th>Index</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Compulsory Area</strong></td>
<td></td>
</tr>
<tr>
<td>Advanced Seminar Quantum Engineering</td>
<td>1</td>
</tr>
<tr>
<td>Interdisciplinary aspects of quantum technologies</td>
<td>3</td>
</tr>
<tr>
<td>Master's Thesis</td>
<td>5</td>
</tr>
<tr>
<td>Research Project - QE</td>
<td>7</td>
</tr>
<tr>
<td><strong>Compulsory Elective Area</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Adaptation</strong></td>
<td></td>
</tr>
<tr>
<td>Mathematics III - Differential equations</td>
<td>9</td>
</tr>
<tr>
<td>Integrated Analog Circuits</td>
<td>12</td>
</tr>
<tr>
<td>Introduction to Microwave Engineering</td>
<td>15</td>
</tr>
<tr>
<td>Introduction to Quantum Engineering</td>
<td>17</td>
</tr>
<tr>
<td>Mathematical Methods in Material Science</td>
<td>20</td>
</tr>
<tr>
<td>Quantum Mechanics</td>
<td>22</td>
</tr>
<tr>
<td>Signals and Systems</td>
<td>24</td>
</tr>
<tr>
<td><strong>Quantum Physics</strong></td>
<td></td>
</tr>
<tr>
<td>Condensed Matter Theory A: Quantum Mechanics on Macroscopic Scales</td>
<td>26</td>
</tr>
<tr>
<td>Condensed Matter Theory B: Quantum Transport and Topology</td>
<td>28</td>
</tr>
<tr>
<td>Experimental Quantum Optics</td>
<td>30</td>
</tr>
<tr>
<td>Introduction to Nuclear Magnetic Resonance</td>
<td>32</td>
</tr>
<tr>
<td>Introduction to Quantum Electronics</td>
<td>35</td>
</tr>
<tr>
<td>Matter Wave Optics</td>
<td>37</td>
</tr>
<tr>
<td>Open Quantum Systems</td>
<td>39</td>
</tr>
<tr>
<td>Quantum Machine Learning</td>
<td>41</td>
</tr>
<tr>
<td>Quantum Computing</td>
<td>43</td>
</tr>
<tr>
<td>Quantum Computing</td>
<td>45</td>
</tr>
<tr>
<td>Quantum Sensing I</td>
<td>47</td>
</tr>
<tr>
<td>Quantum Sensing II</td>
<td>50</td>
</tr>
<tr>
<td>Quantum theory of macroscopic mechanical systems</td>
<td>53</td>
</tr>
<tr>
<td>Seminar Quantum Sensing and Metrology</td>
<td>55</td>
</tr>
<tr>
<td>Seminar Ultracold Quantum Gases</td>
<td>57</td>
</tr>
<tr>
<td>Theoretical Quantum Optics</td>
<td>59</td>
</tr>
<tr>
<td>Theory of Quantum Information</td>
<td>61</td>
</tr>
<tr>
<td>Ultracold Quantum Gases</td>
<td>63</td>
</tr>
<tr>
<td><strong>Electrical Engineering</strong></td>
<td></td>
</tr>
<tr>
<td>Advanced Quantum Engineering</td>
<td>65</td>
</tr>
<tr>
<td>Applied Information Theory</td>
<td>68</td>
</tr>
<tr>
<td>Laboratory Semiconductor Technology</td>
<td>71</td>
</tr>
<tr>
<td>Integrated Broadband Circuits</td>
<td>73</td>
</tr>
<tr>
<td>Integrated High-Frequency Circuits</td>
<td>75</td>
</tr>
<tr>
<td>Integrated Interface Circuits</td>
<td>77</td>
</tr>
</tbody>
</table>
Microwave System Design 80
Optical Communications 82
Quantum Sensing I 85
Quantum Sensing II 88
Technology for Micro- and Nanostructures 91

Mobility and Subject-Specific Specialisation
Big Data Analytics - Methods and Applications 93
Data Mining 96
Founder's Garage I - Businessplan 98
Founder's Garage II - Accelerator 100
Industrial Internship I 102
Industrial Internship II 104
Research Internship 106
Successful Project Management - Fundamentals 108

Complementary Area
Additive Key Qualifications I 110
Additive Key Qualifications II 112
Additive Key Qualifications III 114
Additive Key Qualifications IV 116
## Advanced Seminar Quantum Engineering

**Modules referring to Compulsory Area**

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<td>Attendance time</td>
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<tr>
<td>Language of instruction</td>
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<tr>
<td>Duration</td>
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<td>Cycle</td>
<td>each Summer Semester</td>
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<tr>
<td>Coordinator</td>
<td>Dean of Physics Studies</td>
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<tr>
<td>Instructor(s)</td>
<td>All physics lecturers</td>
</tr>
<tr>
<td>Allocation of study programmes</td>
<td>Quantum Engineering M.Sc., 1st or 2nd Semester</td>
</tr>
<tr>
<td>Recommended prerequisites</td>
<td>B.Sc. degree in Physics or Electrical Engineering</td>
</tr>
</tbody>
</table>
| Learning objectives | Students who have successfully passed this module  
  - are able to research a quantum technology related subject from a scientific point of view in the library, in databases and journals.  
  - have acquired the ability to structure scientific content and to present it in a lecture in compliance with a time schedule.  
  - have learned to defend their point of view in a scientific discussion. |
| Syllabus           | Each semester, several seminars are offered on changing topics from experimental and theoretical physics or related areas of research. |
| Literature         | tba        |
| Teaching and learning methods | Depending on each topic. |
| Workload           | 20 h Seminar (attendance)  
  70 h Talk preparation  
  Total: 90 hours |
<table>
<thead>
<tr>
<th>Assessment</th>
<th>The module examination consists of completing an assignment on a given topic and a graded oral presentation of the results and participation in the discussion.</th>
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<tbody>
<tr>
<td>Grading procedure</td>
<td>The module grade is equal to the examination grade.</td>
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<tr>
<td>Basis for</td>
<td>Preparation of scientific lectures and presentation of own results.</td>
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</table>
Interdisciplinary aspects of quantum technologies
Modules referring to Compulsory Area

**Code** 8802875526

**ECTS credits** 3

**Attendance time** 2

**Language of instruction** English

**Duration** 1

**Cycle** each Winter Semester

**Coordinator** Dean of Physics Studies

**Instructor(s)** Prof. Dr. Fedor Jelezko, Prof. Dr. Claus Braxmaier

**Allocation of study programmes** Quantum Engineering M.Sc., compulsory area, 1st Semester

**Recommended prerequisites** -

**Learning objectives** Students who successfully pass this module understand basic to advanced topics of quantum metrology, cryptography, and computing and are able to interpret and analyze information on these topics.

**Syllabus** Virtual experiments with Qiskit:
- Getting started with Qiskit and performing a photon polarization experiment.
- Quantum coin toss experiment.
- Performing a quantum entanglement experiment.
- Performing a quantum teleportation experiment.
- Quantum random number generation experiment.
- Experiment with depolarizing noise.

Seminar / Portfolio Quantum Technology

Precision limits in quantum metrology.

Quantum cryptography

Quantum computing with ions

Quantum computing with spins in solid state systems
<table>
<thead>
<tr>
<th>Literature</th>
<th>tba</th>
</tr>
</thead>
<tbody>
<tr>
<td>Teaching and learning methods</td>
<td>2 SWS, Lecture</td>
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<tr>
<td>Workload</td>
<td>30 h lecture (attendance)</td>
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<td></td>
<td>60 h self-study</td>
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<td>Assessment</td>
<td>The module examination consists of a graded written or oral examination, depending on the number of participants. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.</td>
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<td>Grading procedure</td>
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**Master's Thesis**
Modules referring to Compulsory Area

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<td>Language of instruction</td>
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<td>Duration</td>
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</tr>
<tr>
<td>Cycle</td>
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<td>Coordinator</td>
<td>Dean of Physics Studies</td>
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<tr>
<td>Instructor(s)</td>
<td>All physics and electrical engineering lecturers</td>
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<tr>
<td>Allocation of study programmes</td>
<td>Quantum Engineering M.Sc., Final projects, 4th semester.</td>
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<tr>
<td>Recommended prerequisites</td>
<td>Formal requirements:</td>
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<tr>
<td></td>
<td>Passing the module &quot;Research Project - QE&quot; and the acquisition of at least 75 ECTS.</td>
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<tr>
<td></td>
<td>Approval of the Examination Board that the topic meets the scientific requirements of the degree program (FSPO §8).</td>
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<tr>
<td>Recommended prior knowledge: Lectures from the subject area of the Master's thesis.</td>
<td></td>
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<tr>
<td>Learning objectives</td>
<td>The students</td>
</tr>
<tr>
<td></td>
<td>• have acquired the competence to work independently on a topic from current research in quantum engineering and to develop their own solutions.</td>
</tr>
<tr>
<td></td>
<td>• are able to write a scientific written elaboration on the results obtained.</td>
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<tr>
<td></td>
<td>• are able to justify their solutions in a scientific discussion and present their own point of view convincingly.</td>
</tr>
<tr>
<td></td>
<td>• have learned to integrate themselves into a research team.</td>
</tr>
<tr>
<td>Syllabus</td>
<td>• Carrying out an experimental or theoretical research project</td>
</tr>
<tr>
<td></td>
<td>• Evaluation of the results obtained</td>
</tr>
<tr>
<td></td>
<td>• Discussion of the results in connection with the specialist literature</td>
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</table>
- Documentation of the research project

<table>
<thead>
<tr>
<th>Literature</th>
<th>tba</th>
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</thead>
</table>

<table>
<thead>
<tr>
<th>Teaching and learning methods</th>
<th>Research work carried out at one of the Institutes of Physics or Electrical Engineering. It can also be carried out externally on request. The maximum processing time is 6 months.</th>
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<table>
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<tr>
<th>Workload</th>
<th>900 h</th>
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<table>
<thead>
<tr>
<th>Basis for</th>
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Research Project - QE
Modules referring to Compulsory Area

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<td>Attendance time</td>
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<td>Language of instruction</td>
<td>English</td>
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<tr>
<td>Duration</td>
<td>1</td>
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<tr>
<td>Cycle</td>
<td>each Semester</td>
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<tr>
<td>Coordinator</td>
<td>No English version available yet.</td>
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<tr>
<td>Instructor(s)</td>
<td>All professors in the selected institute.</td>
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<tr>
<td>Allocation of study programmes</td>
<td>Quantum Engineering M. Sc., compulsory area, 3rd semester</td>
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<tr>
<td>Recommended prerequisites</td>
<td>Skills in Quantum Physics and Electrical Engineering.</td>
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Learning objectives

- Students who successfully passed this module
  - Learn to familiarize themselves with a selected area of the current international research.
  - Can search and understand international scientific literature (information competence).
  - Know the rules of good scientific practice.

Syllabus

- Search of suitable scientific literature and elaboration of the theoretical foundations
- Concrete planning of the research project in collaboration with a team and the supervisor
- Accomplishment of experimental or theoretical preliminary investigation
- Presentation of the research project and intermediate results in a group seminar

Literature

- tba

Teaching and learning methods

- Research project to be carried out in either the department of Physics or Engineering of Ulm University or any cooperating facility.
<table>
<thead>
<tr>
<th><strong>Workload</strong></th>
<th>450 hours</th>
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</thead>
<tbody>
<tr>
<td><strong>Assessment</strong></td>
<td>The module examination consists of a graded written elaboration.</td>
</tr>
<tr>
<td><strong>Grading procedure</strong></td>
<td>The module grade is equal to the examination grade.</td>
</tr>
<tr>
<td><strong>Basis for</strong></td>
<td>Master's thesis</td>
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</table>
Mathematics III - Differential equations
Modules referring to Adaptation

Code 8802876031

ECTS credits 5

Attendance time 4

Language of instruction German

Duration 1

Cycle each Winter Semester

Coordinator Dean of Studies of Mathematics

Instructor(s) Lecturers of Mathematics

Allocation of study programmes
Computational Science and Engineering, B.Sc., FSPO 2019, elective module in Mathematics
Electrical Engineering and Information technology, B.Sc., FSPO 2022, elective module in Mathematics
Communications and Computer Engineering, B.Sc., FSPO 2017, elective module in Mathematics
Physics, B.Sc., FSPO 2019, elective module in Mathematics
Physics and Management, B.Sc., FSPO 2019, elective module in Mathematics

Recommended prerequisites
• Knowledge and application of differential and integral calculus for functions of one and more variables, esp.
  • Integration (single and multiple integrals)
  • derivatives, partial derivatives
  • special functions
• Knowledge and application of linear algebra, esp. matrix calculation
• Dealing with mathematical proofs and proof techniques

Learning objectives
The students
• know the essential terms and statements on the topics given in the module contents.
• can set up and solve important 1st order differential equations, esp.
  • linear differential equation
  • Bernoulli differential equation
  • differential equation with separated variables
  • Exact differential equation
  • Euler homogeneous differential equation
  • Clairaut differential equation
can use Picard-Lindelöf's existence theorem to perform a power series approach to solve differential equations.
- know the connection between systems of differential equations of 1st order and differential equations of higher order
- can set up and solve systems of differential equations of 1st order.
- can set up and solve systems of differential equations of higher order.
- know different mathematical proof techniques and can select and apply them.
- are able to argue mathematically-logically and formally in speech and writing and to visualise their work.

Syllabus
- special differential equations of 1st order
- Existence theorems for solutions of differential equations
- Systems of 1st order differential equations
- Differential equations of higher order
- Boundary and eigenvalue problems (optional)
- Qualitative theory (optional)
- Distributions (optional)

Literature

Teaching and learning methods
Höhere Mathematik III - Differenzialgleichungen (tutorial, optional) (1 SWS), Höhere Mathematik III - Differenzialgleichungen (exercise) (1 SWS), Höhere Mathematik III - Differenzialgleichungen (lecture) (3 SWS)

Workload
48 hours Lecture (attendance)
16 hours exercises (attendance)
86 hours self-study and exam preparation
Total: 150 hours

Assessment
The module examination consists of a graded written examination. Participation in the examination requires an ungraded study achievement. The type, content and scope of the study achievement will be announced in good time in the course information and the course catalogue.

Grading procedure
The module grade is equal to the examination grade.
Basis for
Integrated Analog Circuits
Modules referring to Adaptation

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<tr>
<td>Language of instruction</td>
<td>English (Summer Term) / German (Winter Term)</td>
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<tr>
<td>Duration</td>
<td>1</td>
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<tr>
<td>Cycle</td>
<td>each Semester</td>
</tr>
<tr>
<td>Coordinator</td>
<td>Prof. Dr.-Ing. Maurits Ortmanns</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>Prof. Dr.-Ing. Maurits Ortmanns</td>
</tr>
</tbody>
</table>

**Allocation of study programmes**
- Electrical Engineering and Information Technology, M.Sc, Wahlmodul
- Electrical Engineering and Information Technology, M.Sc, PO2014/17 Kernmodul
- Informationssystemtechnik, M.Sc, PO2014/17, Kernmodul
- Communication and Information Technology, M.Sc., PO2015/2017, Track
- Communications Circuits and Systems, Compulsory Module
- Communication and Information Technology, M.Sc., PO2015/2017, Track
- Communications Engineering, Elective Module

**Recommended prerequisites**
Basic knowledge of semiconductor devices, analog circuits, system and control theory (s-syntax, Bode diagram, feedback systems, stability criteria) and signal processing.

**Learning objectives**
The students differentiate various semiconductor devices and technologies. They compare the behavior and application of the MOST and the BJT. They are able to compare various compact models. The students are able to describe the behavior of the MOS transistor, explain its operation and describe the impact and influence of electrical, manufacturing and environmental non-idealities. They describe and analyze a transistor level circuit using small signal parameters and derive transfer functions for the linearized model. The students differentiate the operation and application of single stage amplifiers and use circuit techniques for gain enhancement. They adopt these methods to design and analyze differential amplifiers. They use advanced concepts for frequency compensation and stabilization. The students can compare the advantages and application of several multistage differential amplifier concepts, analyze and design those amplifiers. They use circuit simulators in order to design these single stage and differential amplifiers for a given specification. The students describe the origin of electronic noise, analyze simple circuits concerning noise contribution, adopt the principle of input referred noise in amplifiers, and explain design based as well
as architectural noise reduction techniques. The students describe the concept of switched capacitor circuits, analyze their behavior and apply them for analog signal processing. They are able to apply the principles of analog integrated circuit design to further applications. They describe and compare the functionality of various concepts for analog-to-digital and digital-to-analog converters. The students describe the principal of oversampling and noise shaping and apply this to the concept of sigma-delta modulators.

**Syllabus**
- Devices and non-idealities
- MOS and Bipolar transistors including signal parameters and non-idealities
- On-chip bias generation
- Review of basic analog circuits
- Single-stage CMOS amplifiers
- Enhanced CMOS amplifier concepts
- Two-stage CMOS amplifiers with frequency compensation
- Introduction to electronic noise
- Switched-Capacitor Circuits
- A/D and D/A converters

**Literature**
- Baker, R.J. “CMOS Circuit Design, Layout, and Simulation”, Wiley
- Sansen, W. „Analog Design Essentials“, Springer

**Teaching and learning methods**
Lecture "Integrierte Analogschaltungen" (Integrated Analog Circuits), 3 SWS
Practical Exercises "Integrierte Analogschaltungen" (Integrated Analog Circuits), 1 SWS

**Workload**
Active Time: 60 h
Preparation and Evaluation: 120 h
Sum: 180 h

**Assessment**
The module examination consists of a graded written or oral examination, depending on the number of participants. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

**Grading procedure**
The module grade is equal to the examination grade.

**Basis for**
- Project: Analog CMOS Circuit Design
- Lecture: Circuit Design in Nanometer-Scaled CMOS Technologies
- Lecture: Integrated Interface Circuits
- Elective Modules
- Master-Thesis
# Introduction to Microwave Engineering

**Modules referring to Adaptation**

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<tr>
<td>Duration</td>
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</tr>
<tr>
<td>Cycle</td>
<td>each Summer Semester</td>
</tr>
<tr>
<td>Coordinator</td>
<td>Prof. Dr.-Ing. Christian Waldschmidt</td>
</tr>
</tbody>
</table>
| Instructor(s) | Prof. Dr.-Ing. Christian Waldschmidt  
Prof. Dr.-Ing. Christian Damm  
Dr.-Ing. Frank Bögelsack |
| Allocation of study programmes | Communications Technology, M.Sc., Compulsory Module  
Electrical Engineering and Information Technology |
| Recommended prerequisites | - |
| Learning objectives | After successful completion of this module, students are able to describe voltage and current waves and to understand the relation to plane waves. Using the Smith chart the students are able to characterize complex impedances and to design matching networks. They are familiar with the method of the signal flow graph to describe linear time-invariant n-ports with means of scattering parameters. The students have a good knowledge of the basics of the field theory and the calculation of losses using the Skin effect approximation. They are able to identify and to describe important properties of components used in RF and microwave engineering. They are familiar with noise analysis of linear matched two-ports as well as of the concatenation of circuits using the chain noise figure. They are able to design Butterworth and Chebyshev filters. They are capable to find new approaches for unknown problems in RF and microwave engineering area. |
| Syllabus | The module covers in particular the following subjects:  
- Basics of the electromagnetic field theory  
- Plane waves  
- Current and voltage waves on (TEM-) lines, power waves |
- Relations of these waves to electromagnetic waves
- Skin effect
- Reflection of waves at complex line-terminations
- Smith chart
- Impedance transformation by lines and other circuit components
- Realistic components
- Description of linear time-invariant wave-N-ports by scattering parameters
- Signal flow graph
- Components like filters, couplers, amplifiers (overview, not a detailed description)
- Electronic noise
- Basics on antennas, antenna types

**Literature**
- Lecture handout
- Text books: see lecture handout

**Teaching and learning methods**
Lecture “Introduction to Microwave Engineering”, 3 SWS
Exercise “Introduction to Microwave Engineering”, 1 SWS

**Workload**
Active Time: 60 h
Preparation and Evaluation: 45 h
Self-Study: 45 h
Sum: 150 h

**Assessment**
The module examination consists of a graded written or oral examination, depending on the number of participants. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

**Grading procedure**
The module grade is equal to the examination grade.

**Basis for**
This module is a prerequisite for the modules:
- Introduction to Microwave Communication Systems,
- Lab RF Engineering
Introduction to Quantum Engineering
Modules referring to Adaptation

<table>
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<td>Duration</td>
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<tr>
<td>Cycle</td>
<td>each Winter Semester</td>
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<tr>
<td>Coordinator</td>
<td>Prof. Claus Braxmaier</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>Dr. Lisa Wörner</td>
</tr>
</tbody>
</table>
| Allocation of study programmes | Electrical Engineering and Information Technology M.Sc.  
Communications and Computer Engineering M.Sc.  
Communication and Information Technology M.Sc.  
Quantum Engineering M.Sc. |
| Recommended prerequisites | Solid Basics in Physics (for instance: Modul Physik für Ingenieure) |
| Learning objectives | Students, that have completed this module successfully,  
• Have an overview over basic quantum mechanical phenomena  
• Know about the applications of quantum mechanical phenomena, i.e. for sensing, material research, communication, and computing  
• Have an overview over quantum technologies  
• Know about current developments in quantum engineering and supporting technologies, i.e. vacuum systems, laser technologies, metrology, microsystems, and materials  
• Know the basics of technology development and market evaluation  
• Are able to judge specific challenges  
• Can develop solutions to complex engineering challenges  
• Have strategies to transfer technology to industry  
• Can work at the interface between physics and engineering  
• Widen independently their knowledge in quantum technologies and have strategies for efficient literature search |
Syllabus

In this lecture the following content will be taught:

- Foundation Principles of quantum mechanical:
  - Wave-Particle Duality, Basics of interferometry, single particle experiments and interpretation
  - Schrödinger's Equation, wave function, and their implication
  - Atom spectra and Atom models
  - Spin, Bose-Einstein Condensates, Fermi-Dirac Distribution
  - Entanglement
- Prerequisites for the application of specific phenomena and the realization: i.e.: coherence, thermal and structural stability, materials, signal strength and signal integrity
- Application if quantum mechanics for: i.e.: mobility, Earth observation, navigation, communication, and sensing
- Overview over necessary technologies: i.e.: vacuum technology, micro systems, laser technology

Literature

F. Schwabl: Quantum Mechanics and Advanced Quantum Mechanics
T. Fließbach: Quantenmechanik
I.V. Hertel, C.-P. Schulz, Atome Moleküle und optische Physik
W. Demtröder, Experimentalphysik 3
A.M. Zagoskin, Quantum Engineering
NASA Systems Engineering Handbook Rev. 2
Current Publications and articles
Script and Slides from the lecture

Teaching and learning methods

Lecture Introduction to Quantum Engineering: 2 SWS

Workload

30 h Lecture
90 h Self-study and preparation for the exam
Total: 120 h

Assessment

The module examination consists of a graded written or oral examination, depending on the number of participants. If a specified academic work is achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.
<table>
<thead>
<tr>
<th><strong>Grading procedure</strong></th>
<th>The module grade is equal to the examination grade.</th>
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<tbody>
<tr>
<td><strong>Basis for</strong></td>
<td>Advanced Quantum Engineering</td>
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</table>
Mathematical Methods in Material Science
Modules referring to Adaptation

Code 8802872382

ECTS credits 5

Attendance time 4

Language of instruction English

Duration 1

Cycle each Winter Semester

Coordinator Dean of Physics Studies

Instructor(s) Dr. Ressa Said, Dr. Genko Genov

Allocation of study programmes Quantum Engineering M.Sc., Biophysics M.Sc., adaptation module, 1st semester

Recommended prerequisites None

Learning objectives Students who successfully passed this module
- have an overview on essential mathematical methods for the solution of generic problems in Physics.
- have trained to analyze and solve physical problems quantitatively.

Syllabus This course gives an overview of essential mathematical methods for the solution of generic problems in Physics. Specific examples of important physical applications will be given. The course aims to provide the student with the expected mathematical competency for further courses in different areas of Physics.
- Application of complex numbers and variables
- Fundamentals of matrices and its applications
- Further differentials and integrals, differential equations
- Fourier Series and Transform, Laplace Transform
- Finite Difference and Spectral Solutions
- Calculus of Variations
| **Literature** | Bibliographical references will be given to the students for each different topic addressed in the course. |
| **Teaching and learning methods** | Lecture (3 hours per week), Exercise (1 hour per week) |
| **Workload** | 45 hours lecture  
15 hours exercise  
90 hours self-study and exam preparation  
Total: 150 hours |
| **Assessment** | The grade of the module will be the grade of the written exam. No prerequisites are necessary for exam registration. |
| **Grading procedure** | The grade of the module will be the grade of the exam. |
| **Basis for** | All other modules |
Quantum Mechanics
Modules referring to Adaptation

Code 8802870366

ECTS credits 8

Attendance time 6

Language of instruction German and English

Duration 1

Cycle each Summer Semester

Coordinator Dean of Physics Studies

Instructor(s) Prof. Dr. Joachim Ankerhold, apl. Prof. Dr. Matthias Freyberger, Prof. Dr. Susana Huelga, Prof. Dr. Martin Plenio, Prof. Dr. Wolfgang Schleich

Allocation of study programmes Physik B.Sc., compulsory module, 4th semester
Wirtschaftsphysik B.Sc., compulsory module, 4th semester
Electrical Engineering and Information Technology
Computational Science and Engineering, B.Sc.

Recommended prerequisites Learning outcomes of Theoretical Mechanics, Mathematics I and II. Mathematics III - Differential Equations (should at least be heard in parallel)

Learning objectives Students who have successfully passed the module

- know the conceptual differences between classical and quantum mechanics.
- are mathematically proficient in the formalism of quantum mechanics and can solve time-independent and time-dependent problems.
- are able to treat typical systems, if necessary also with suitable approximation methods.

Syllabus In this module the following contents are taught:

- Particles and waves
- Schrödinger equation
- one-dimensional potential problems
- Postulates of quantum mechanics
- mathematical formalism and Dirac notation
- harmonic oscillator
• radial symmetric problems and hydrogen atom
• stationary perturbation theory
• entanglement

<table>
<thead>
<tr>
<th>Literature</th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Cohen- Tannoudji, Quantenmechanik Bd. 1, Bd. 2 (teilweise)</td>
<td>Schwabl, Quantenmechanik</td>
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<td>Messiah, Quantenmechanik, Bd. 1</td>
<td>Fick, Einführung in die Grundlagen der Quantentheorie</td>
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<th>Lecture (4 hours per week)</th>
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<tr>
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<td>Exercise (2 hours per week)</td>
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<tr>
<th>Workload</th>
<th>60 hours lecture (attendance)</th>
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<td></td>
<td>30 hours exercise (attendance)</td>
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<td>150 hours self-study and exam preparation</td>
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| Assessment                       | The module examination consists of a graded written or oral examination, depending on the number of participants. Participation in the examination requires an ungraded study achievement. If a specified academic work is achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The type, content and scope of the study achievement[s] will be announced in good time in the course information and the course catalogue. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date. |

| Grading procedure                | The module grade is equal to the examination grade. |

| Basis for                        | Modules Solid state physics, nuclear, particle and astrophysics, thermodynamics and statistics, advanced methods of quantum mechanics |
## Signals and Systems

*Modules referring to Adaptation*

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<td>Duration</td>
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<td>Cycle</td>
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<td>Coordinator</td>
<td>Prof. Dr.-Ing. Robert Fischer</td>
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<td>Teaching and learning methods</td>
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<tr>
<td>Workload</td>
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<td><strong>Basis for</strong></td>
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Condensed Matter Theory A: Quantum Mechanics on Macroscopic Scales  
Modules referring to Quantum Physics

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<td>Coordinator</td>
<td>Dean of Physics Studies</td>
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<tr>
<td>Instructor(s)</td>
<td>Prof. Dr. Joachim Ankerhold, Dr. Björn Kubala, Dr. Ciprian Padurariu</td>
</tr>
<tr>
<td>Allocation of study programmes</td>
<td>Physics M.Sc., elective</td>
</tr>
<tr>
<td>Recommended prerequisites</td>
<td>Quantum mechanics, solid state physics, thermodynamics/statistics</td>
</tr>
</tbody>
</table>

**Learning objectives**

Students who successfully passed this module

- understand methods and concepts of the description of open classical and quantum mechanical systems.
- understand basic differences in the dynamics of classical and quantum mechanical open systems.
- possess advanced knowledge of quantum statistics.
- are able to read relevant original literature to present it and know current experimental realizations.

**Syllabus**

The lecture explores theoretical and experimental developments in solid state physics over the past twenty years that describe and access quantum mechanical properties on growing length scales and with growing complexity.

Low-temperature properties of condensed matter systems are governed by quantum mechanics. Many-body effects are crucial and may lead to completely new phenomena, determined by the dynamics of new collective degrees of freedom. In superconducting devices, the quantum dynamics of these collective variables can be observed, manipulated and exploited for applications, e.g., for quantum-information technologies. In this course, we will study the physics underlying such devices and introduce tools for their analysis and description.
- Introduction
- Macroscopic quantum oscillator
- Nonlinear oscillator: Josephson junction
- From artificial atoms to circuit-QED
- Basics of open quantum systems: master equation
- Single charge transfer
- From circuit-QED to Josephson photonics

**Literature**
- Michel Devoret, Quantum fluctuations in electrical circuits, Les Houches Lectures, with Uri Vool, arXiv:1610.03438
- Tero T. Heikkilä, The Physics of Nanoelectronics: Transport and Fluctuation Phenomena at Low Temperatures

**Teaching and learning methods**
Lecture (3 hours/week), tutorials (2 hours/week)

**Workload**
- 45 hours lecture (attendance time)
- 30 hours exercise (attendance time)
- 105 hours self-study and exam preparation
- Total: 180 hours

**Assessment**
The module examination consists of a graded written or oral examination, depending on the number of participants. Participation in the examination requires an ungraded study achievement. If a specified academic work is achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The type, content and scope of the study achievement will be announced in good time in the course information and the course catalogue. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

**Grading procedure**
The module grade is equal to the examination grade.

**Basis for**
Research project in the field of condensed matter
Condensed Matter Theory B: Quantum Transport and Topology
Modules referring to Quantum Physics

Code 8802876068
ECTS credits 6
Attendance time 5
Language of instruction English
Duration 1
Cycle Summer Semester every two Years
Coordinator Dean of Physics Studies
Instructor(s) Prof. Joachim Ankerhold, Dr. Björn Kubala, Dr. Ciprian Padurariu
Allocation of study programmes Physics M.Sc., elective module
Recommended prerequisites Quantum Mechanics, Solid State Physics, Thermodynamics/Statistics

Learning objectives Students who successfully passed this module
• understand different regimes of electrical transport in nanoscale systems and corresponding theoretical methods of their description.
• understand how classical transport differs from quantum coherent transport and which new phenomena may appear.
• understand the importance and application of topological arguments in modern quantum transport phenomena.
• are able to read relevant original literature to present it and know current experimental realizations.

Syllabus The laws governing electrical transport change fundamentally, if an electronic device is reduced in size down to the free path of electrons. In the Integer Quantum Hall Effect (IQHE), for instance, resistance no longer changes linearly, but in a stepwise manner, due to the quantized (Landau-)levels for charge transport in a strong magnetic field. Even more drastically is the fractional version of the quantum Hall effect, where new (quasi-)particles carry only a fraction of the elementary charge e.
The discovery of the Integer Quantum Hall effect in 1980, rewarded by the 1985 Nobel prize to Klaus von Klitzing, gives also one of the earliest examples of the importance of topological quantum numbers in condensed matter physics.

In this lecture, we want to explore quantum effects in transport:

From the early experimental observation of conductance quantization and the theoretical picture of Landauer of "transport as transmission" to the recent focus on topological properties and materials, such as topological insulators.

- Tunneling and Scattering Matrix Theory
- Landau-levels and the Integer Quantum Hall Effect
- Fractional Quantum Hall Effect, composite fermions
- Majorana fermions and the Kitaev chain
- Topological quantum numbers

**Literature**

- Scattering theory (G. Lesovik et al.): Scattering matrix approach to the description of quantum electron transport
  Lecture notes by Clive Emary (Newcastle University)
  Lecture notes by Marc Baldo (MIT, OpenCourseWare)
- Quantum Hall effect: Lecture Notes by David Tong (Cambridge) [http://www.damtp.cam.ac.uk/user/tong/qhe.html](http://www.damtp.cam.ac.uk/user/tong/qhe.html)
- Topology: web course on Topology in CM (Anton Akhmerov et al., TU Delft) [https://ocw.tudelft.nl/courses/topology-condensed-matter-concept/](https://ocw.tudelft.nl/courses/topology-condensed-matter-concept/)

**Teaching and learning methods**

Lecture (3 hours/week), tutorials (2 hours/week)

**Workload**

45 hours lecture (attendance time)
30 hours exercise (attendance time)
105 hours self-study and exam preparation
Total: 180 hours

**Assessment**

The module examination consists of a graded written or oral examination, depending on the number of participants. Participation in the examination requires an ungraded study achievement. If a specified academic work is achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The type, content and scope of the study achievement will be announced in good time in the course information and the course catalogue. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

**Grading procedure**

The module grade is equal to the examination grade.

**Basis for**

Research in the field of condensed matter
Experimental Quantum Optics
Modules referring to Quantum Physics

Code 8802872190

ECTS credits 6

Attendance time 6

Language of instruction English

Duration 1

Cycle each Summer Semester

Coordinator Dean of Physics Studies

Instructor(s) Prof. Alexander Kubanek

Allocation of study programmes

Physics M.Sc., elective module, 1st or 2nd semester

Wirtschaftsphysik M.Sc., elective module, 1st - 3rd semester

Advanced Materials M.Sc., compulsory elective module, 1st - 3rd semester

Recommended prerequisites Optics, Atomic Physics, Quantum Mechanics

Learning objectives

Students who successfully passed this module

• are familiar with concepts and techniques used in modern Quantum Optics.
• know the application of Laser physics and the applications of lasers for cavity QED.

Syllabus

• Laser Physics
• Quantum nature of light
• Interaction of light and matter
• Atomic and "atom-like" systems
• Cavity Quantum Electrodynamics
• Current research topics in Quantum Optics (Nonlinear Optics, Quantum Entanglement, Bell’s inequalities, Quantum Teleportation, Quantum Cryptography, Quantum Computing)

Literature Specific literature will be provided throughout the course. In-depth literature research is also part of independent preparation of the student presentations.
Quantum Optics books for general preparation:

- G. Grynberg, A. Aspect and C. Fabre, *Introduction to Quantum Optics*

More specialized books:

- S. Haroche, J. M. Raimond, *Exploring the Quantum*, (Oxford University Press 2006); comment: specialized on cavity QED

### Teaching and learning methods

<table>
<thead>
<tr>
<th>Lecture</th>
<th>3 hours per week</th>
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</thead>
<tbody>
<tr>
<td>Exercise</td>
<td>2 hours per week</td>
</tr>
</tbody>
</table>

### Workload

- 45 hours lecture (attendance time)
- 30 hours exercise (attendance time)
- 105 hours self-study and exam preparation
- Total: 180 hours

### Assessment

The module examination consists of a graded written or oral examination, depending on the number of participants. Participation in the examination requires an ungraded study achievement. If a specified academic work is achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The type, content and scope of the study achievement[s] will be announced in good time in the course information and the course catalogue. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

### Grading procedure

The module grade is equal to the examination grade.

### Basis for

Research in the fields of quantum information and technologies
# Introduction to Nuclear Magnetic Resonance

Modules referring to Quantum Physics

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<td>Language of instruction</td>
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<td>Duration</td>
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<td>Cycle</td>
<td>each Winter Semester</td>
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<td>Dean of Physics Studies</td>
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<tr>
<td>Instructor(s)</td>
<td>Dr. Raiker Witter</td>
</tr>
</tbody>
</table>

## Allocation of study programmes

- Physics M.Sc., D - Examination Field Master Programmes, E - Examination Field General Range of Studies, 1\textsuperscript{st} or 2\textsuperscript{nd} semester

## Recommended prerequisites

- physical chemistry; QM II, atom and molecule physics

## Learning objectives

Students who successfully passed this module:

- are aware of and understand the wide scope, applicability and perspective of NMR spectroscopy across different fields (physics, chemistry and biomedicine);
- have comprehended the Hamiltonian concerning the interactions between electrons and nuclei in context of an external magnetic field (quantum mechanical/chemical approaches incl. perturbation theory);
- know the quantum mechanical framework to understand, describe, and simulate NMR experiments incl. spectra;
- have the basic understanding to interpret spectroscopic findings, material characterisations up to 3D structure determinations and imaging;
- are able to combine the methodology to EPR, Nano-Sensing and Quantum Computing; and
- are able to practically apply the knowledge to advance in other physics subjects (atom/molecule, solid-state and quantum information physics), scientific fields (organic, biomedical, inorganic, physical chemistry) and the wide scope of master theses in natural sciences.

## Syllabus

The following technical contents are taught in this module:
(1) introductory: Stern-Gerlach experiment, Rabi experiment, NMR related noble prices;

(2) theoretically: the spin, wave-function, Schrödinger Equation, electrons-nuclei Hamiltonian with magnetic field incl. perturbation theory, Liouville von Neumann Equation, density operator/matrix, time-evolution operator (propagator), equilibrium vs. excited states, multi-quantum coherences, observation/truncation, rotating frame, average Hamiltonian, irreducible tensor formalism, relaxation (fluctuation, autocorrelation, spectral density, transition rates and relaxation times), product operator formalism, etc.;

(3) experimentally: basic setup (magnetic field incl. gradients, inductive detection, resonance circuit, duplexer, quadrature detection, ADC and computer), signal-to-noise, pulsed experiments, Fourier transformation, spectral fitting, signal assignment, referencing, magic-angle-spinning, rotor-synchronicity, ex-situ, in-situ, operando characterizations incl. basic MRI etc.; and

(4) applied: finally, an entrance to liquid- and solid-state NMR will be given by providing representative examples in organic, biomedical (3D structure determination) and inorganic chemistry (e.g. characterization of battery materials and devices).

Furthermore, a comprehensive introduction into dynamic nuclear polarization (DNP), electron spin resonance (EPR), quantum-sensing and quantum computing will be provided.

Literature

- Understanding NMR Spectroscopy; James Keeler, Wiley, 2010
- Quantum Mechanics Vol. 1 & 2, C. Cohen-Tannoudji et al., 1977
- Spin Dynamics, M. H. Levitt, 2008
- Principles of Magnetic Resonance, C. P. Slichter, 1978
- Principles of Nuclear Magnetism, A. Abragam, Clarendon Press, 1983
- Introduction to Solid-State NMR Spectroscopy, Melinda J. Duer, John Wiley & Sons, 2005
- Applications of NMR Spectroscopy, Atta-ur-Rahman and M. Iqbal Choudhary, Bentham, 2015
- Handbook of High Field Dynamic Nuclear Polarization, Vladimir K. Michaelis et al., Wiley, 2020
- NMR Quantum Information Processing, Ivan Oliveira et al., Elsevier Science, 2011
- Lectures on General Quantum Correlations and their Applications (Quantum Science and Technology), Felipe Fernandes Fanchini et al., Springer, 2017
- Electron Spin Resonance (ESR) Based Quantum Computing (Biological Magnetic Resonance Book 31), Takeji Takui, Lawrence Berliner et al., 2016

Teaching and learning methods

lecture (3 hours per week) with problem sheet solving and seminar (2 hours per week) for solutions’ presentation incl. Q&A session (2 h/w).
**Workload**

- 45 hours lecture (attendance time)
- 30 hours seminar (attendance time)
- 105 hours self-study
- Total: 180 hours

**Assessment**

The module examination consists of a graded written or oral examination, depending on the number of participants. Participation in the examination requires an ungraded study achievement. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

**Grading procedure**

The module grade is equal to the examination grade.

**Basis for**

It can be considered being a versatile basis for a wider range of follow-up topics, incl. master theses, also beyond NMR, due to the fact that this spectroscopy is presented in it’s over decades and noble prices developed overarching character, providing settled synergies from theory, experiment to applications in physics, chemistry and biomedicine.
## Introduction to Quantum Electronics

**Modules referring to Quantum Physics**

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<td>Dean of Physics Studies</td>
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<td>Dr. Siyushev</td>
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<tr>
<td>Allocation of study programmes</td>
<td>M. Sc. Physics, elective module, 1\textsuperscript{st} or 2\textsuperscript{nd} semester</td>
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<tr>
<td>Recommended prerequisites</td>
<td>Classical electrodynamics</td>
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</table>

### Learning objectives

This course aims to introduce and provide required knowledge on quantum electronics for those who are planning to work in modern optics and utilize laser field for research and development. This course discusses interaction of coherent fields with atomic systems, specificity of the gain medium, transition rates, etc. Special place in this course is dedicated to the detailed theoretical description of laser cavities. The course is finishing by consideration of the most common laser systems and their specific characteristics.

### Syllabus

- Spontaneous and stimulated transitions, Einstein coefficients, coherence of stimulated emission
- Light-matter interaction, transition probability
- Spectral line shape, inhomogeneous and homogeneous broadening
- Absorption and amplification, gain medium, saturation
- Laser oscillations, feedback, lasing threshold, resonant conditions
- Gaussian beams, beam’s caustics, evolution of Gaussian beams
- Optical cavities, stability criterion, cavity losses
- Lasing on several longitudinal modes, mode locking, pulsed regime, Q-switching
- The most common lasers, main excitation methods, gas lasers, solid state lasers, semiconductor lasers, dye lasers, free-electron lasers
| Literature            | • Orazio Svelto, Principles of Lasers (Springer, 2010)  
|                      | • Amnon Yariv, Quantum Electronics (John Wiley and Sons 1988)  
|                      | • Amnon Yariv, Introduction to Optical Electronics (Holt, R. & W 1971)  |
| Teaching and learning methods | Lecture (2 h/week)  |
| Workload              | 30 hours Lecture (attendance)  
|                      | 60 hours Self-study and exam preparation  
|                      | Total: 90 hours  |
| Assessment            | The module examination consists of a graded written or oral examination, depending on the number of participants.  |
| Grading procedure     | The module grade is equal to the examination grade.  |
| Basis for             | Research in Quantum Optics  |
Matter Wave Optics
Modules referring to Quantum Physics

Code 8802877079

ECTS credits 6

Attendance time 5

Language of instruction English

Duration 1

Cycle each Winter Semester

Coordinator Dean of Physics Studies

Instructor(s) Dr. Christian Brand

Allocation of study programmes
Physics M.Sc., elective module.
Quantum Physics M.Sc., elective module.

Recommended prerequisites -

Learning objectives Students who have successfully completed the module,
• have an overview of the physics of matter-waves.
• know different methods to prepare, manipulate and detect matter-waves.
• understand the advantages and benefits of matter-waves in metrology.

Syllabus This lecture series gives a comprehensive introduction to the physics of matter-waves, covering particles from electrons up to massive molecules. In the course of the series the students learn techniques how to prepare, manipulate, and detect matter-waves. We will discuss the fundamental concepts of matter-wave experiments and show how they are harnessed for metrology, inertial sensing, and the search for new physics.

• Beam splitter methods
• Interferometer concepts
• Dephasing and decoherence
• Metrology and sensing

Literature tba
<table>
<thead>
<tr>
<th>Teaching and learning methods</th>
<th>Lecture (3 hours per week)</th>
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<td>Exercise (1 hours per week)</td>
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<tr>
<th>Workload</th>
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<td>30 hours exercise (attendance time)</td>
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<td>105 hours self-study</td>
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<td></td>
<td>Total: 180 hours</td>
</tr>
</tbody>
</table>

| Assessment                   | The module examination consists of a graded written or oral examination, depending on the number of participants. Participation in the examination requires an ungraded study achievement. If a specified academic work is achieved, a grade bonus is awarded in accordance with §24 (3) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The type, content and scope of the study achievement[s] will be announced in good time in the course information and the course catalogue. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date. |

<table>
<thead>
<tr>
<th>Grading procedure</th>
<th>The module grade is equal to the examination grade.</th>
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</table>

| Basis for                    | -                                                   |
# Open Quantum Systems

Modules referring to Quantum Physics

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<thead>
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<tr>
<td>Attendance time</td>
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</tr>
<tr>
<td>Language of instruction</td>
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<tr>
<td>Duration</td>
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<tr>
<td>Cycle</td>
<td>each Winter Semester</td>
</tr>
<tr>
<td>Coordinator</td>
<td>Dean of Physics Studies</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>Prof. Susana Huelga</td>
</tr>
</tbody>
</table>

**Allocation of study programmes**
- Physics M.Sc., elective module, 1st or 2nd semester

**Recommended prerequisites**
- Quantum mechanics

**Learning objectives**
- Students who successfully passed this module
  - can describe theoretically an open quantum system.
  - are familiar with the theoretical concepts of coherence and decoherence in a quantum system.

**Syllabus**
- description of systems
- environmental interactions and dynamics of open quantum systems
- coherent dynamics
- decoherence and decoherence
- relation to current experiments

**Literature**
- Preskill, Quantum Computation Lecture Notes

**Teaching and learning methods**
- Lecture (3 hours per week)
- Tutorials (2 hours per week)
| **Workload** | 45 hours lecture (attendance time)  
30 hours tutorials (attendance time)  
105 hours self-study and exam preparation  
Total: 180 hours |
| **Assessment** | The module examination consists of a graded written or oral examination, depending on the number of participants. Participation in the examination requires an ungraded study achievement. If a specified academic work is achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The type, content and scope of the study achievement[s] will be announced in good time in the course information and the course catalogue. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date. |
| **Grading procedure** | The module grade is equal to the examination grade. |
| **Basis for** | Research in the fields of quantum information and technologies |
Quantum Machine Learning
Modules referring to Quantum Physics

Code 8802875168

ECTS credits 4

Attendance time 3

Language of instruction English

Duration 1

Cycle irregular

Coordinator Dean of Physics Studies

Instructor(s) Dr. Sabine Wölk

Allocation of study programmes Physics M.Sc., elective module
Wirtschaftsphysik M.Sc., elective module

Recommended prerequisites Theoretical Quantum Mechanics (mandatory), Theory of Quantum Information (helpful but not required)

Learning objectives Students who successfully passed this module
• are familiar with basic concepts of classical machine learning such as supervised, unsupervised and reinforcement learning
• know examples of quantum algorithm which provide advantages for machine learning

Syllabus
• Neural networks
• Support vector machines
• Restricted Boltzmann machine
• Reinforcement learning
• Quantum annealing
• Amplitude amplification

Literature
• Goodfellow, Bengio and Courville, "Deep Learning", MIT Press, 2016;
• Lämmel and Cleve, "Künstliche Intelligenz", Hanser Verlag, 2008;
• J. Biamonte et al., "Quantum Machine Learning", Nature 549, 195 (2017);
<table>
<thead>
<tr>
<th><strong>Teaching and learning methods</strong></th>
<th>Lecture (2 hours per week)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Exercise (1 hours per week)</td>
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<table>
<thead>
<tr>
<th><strong>Workload</strong></th>
<th>30 hours lecture (attendance time)</th>
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<tbody>
<tr>
<td></td>
<td>15 hours exercise (attendance time)</td>
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<tr>
<td></td>
<td>75 hours self-study</td>
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<tr>
<td></td>
<td>Total: 120 hours</td>
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</table>

| **Assessment**                | The module examination consists of a graded written or oral examination, depending on the number of participants. |

| **Grading procedure**         | The module grade is equal to the examination grade. |

| **Basis for**                 | Research in the field of Quantum Technologies. |
Quantum Computing
Modules referring to Quantum Physics

<table>
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<td>Dean of Physics Studies</td>
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<tr>
<td>Instructor(s)</td>
<td>Prof. Dr. Jacobo Torán</td>
</tr>
</tbody>
</table>

**Allocation of study programmes**
- Informatik, M.Sc., theoretical and mathematical methods in computer science
- Mathematics, M. Sc., FSPO 2024, compulsory elective modules in the subsidiary subject Computer Science
- Mathematics, M. Sc., FSPO 2024, compulsory elective modules in the multidisciplinary subsidiary subject
- Medieninformatik, M.Sc., theoretical and mathematical methods in computer science
- Software-Engineering, M.Sc., theoretical and mathematical methods in computer science
- Quantum Engineering, M.Sc. elective module
- Mathematics and Management, M. Sc., FSPO 2024, compulsory elective modules in Computer Science

**Recommended prerequisites**
Lectures on formal basics in the Bachelor's programme

**Learning objectives**
Students learn the basic principles of quantum computing. They are familiar with the formal foundations for quantum computers and the most important algorithms for such models.

**Syllabus**
- Quantum models
- Grover's search algorithm
- Shor's algorithm for factorisation
- Finite quantum automata
- Quantum communication and cryptology
- Quantum error-correcting codes
**Literature**

- Lecture notes

**Teaching and learning methods**

Lecture Quantum Computing, 2 classroom hours  
Exercise Quantum Computing, 1 classroom hour

**Workload**

- Attendance: 60 h
- Self-study: 120 h
- Total: 180 h

**Assessment**

The module examination consists of a graded written or oral examination, depending on the number of participants. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

**Grading procedure**

The module grade is equal to the examination grade.

**Basis for**

-
Quantum Computing
Modules referring to Quantum Physics

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<td>Language of instruction</td>
<td>English or German</td>
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<tr>
<td>Duration</td>
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<tr>
<td>Cycle</td>
<td>each Summer Semester</td>
</tr>
<tr>
<td>Coordinator</td>
<td>Dean of Physics Studies</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>Prof. Dr. Birger-Horstmann</td>
</tr>
</tbody>
</table>

Allocation of study programmes
- Physics M.Sc., elective module.
- Wirtschaftsphysik M.Sc., elective module.
- Quantum Engineering M.Sc., elective module.

Recommended prerequisites
Successful participation in a Bachelor course on quantum mechanics is mandatory even though the relevant concepts for quantum computation will be summarized.

Learning objectives
Students who successfully passed this module
- master quantum computing
- know the promises of the most prominent quantum algorithms
- have an idea about quantum error correction
- know about proposals for quantum computing hardware
- understand the concept of quantum simulation
- are capable of programming today’s quantum computers

Syllabus
1. Basics of quantum computing, e.g., quantum circuits, entanglement
2. Quantum algorithms, e.g., quantum fourier transform
3. Fault tolerant quantum computation, e.g., error correction
4. Hardware for quantum computing
5. Noisy intermediate-scale quantum era (NISQ)
6. Quantum simulations, e.g., for quantum chemistry
Literature

- John Preskill, Lecture notes on quantum information theory, available at http://theory.caltech.edu/~preskill/ph229/

Teaching and learning methods

Lecture & Seminar (3 + 2 hours per week)

Workload

- 45 hours lecture
- 30 hours seminar (attendance time)
- 105 hours self-study and exam preparation

Total: 180 hours

Assessment

The module examination consists of a graded written or oral examination, depending on the number of participants. Participation in the examination requires an ungraded study achievement. If a specified academic work is achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The type, content and scope of the study achievement[s] will be announced in good time in the course information and the course catalogue. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

Grading procedure

The module grade is equal to the examination grade.

Basis for

-
Quantum Sensing I
Modules referring to Quantum Physics

Code  8802875481

ECTS credits  4

Attendance time  2

Language of instruction  english

Duration  1

Cycle  each Winter Semester

Coordinator  Prof. Dr. Claus Braxmaier
Lee Kumanchik, Ph.D.

Instructor(s)  Lee Kumanchik, Ph.D.

Allocation of study programmes
Communications and Computer Engineering M.Sc.
Electrical Engineering M.Sc.
Quantum Engineering M.Sc.
Communication and Information Technology M.Sc.
Sensorsystemtechnik M.Sc.
Physics M.Sc.

Recommended prerequisites  Contents of basic physics (e.g. Physics for Engineers module) incl. basics of photonics

Learning objectives  Students who have successfully completed this module,

• have an overview of basic quantum mechanical principles
• know the applications of quantum mechanical phenomena for sensor technology and also for communication and computer technology
• know qualitatively and quantitatively the interaction of quantum states with the environment and know about the higher sensitivity of this and traceability to Planck’s constant
• have a rough overview of current quantum technologies
• have a basic knowledge of measurement techniques including statistical methods of data acquisition, analysis and presentation
• know about the advantages of using quantum sensors in general and in particular to achieve the standard quantum limit and below,
• know the wide range of measurands, such as acceleration, temperature, magnetic field, electric field, pressure, frequency, time, pH, concentration...
• know about the achievable accuracy and sensitivity of the respective method, as well as the interferences on the respective measurement systems
• know the fields of application of quantum sensors in technology, physics, biology, medicine, aerospace and mobility
• know basic methods of microsystems engineering for the development of miniaturized quantum sensors up to lab-on-a-chip.
• are able to work at the interface between physics and engineering science
• independently expand their knowledge in the field of quantum sensor technology and are provided with strategies for literature searches

Syllabus
In this lecture the following technical contents will be taught:
• highest resolution sensing and metrology needs: engineering, physics, biology, medicine, aerospace and mobility.
• Fundamentals of sensor technology, overview of sensory systems and metrology
• fundamental quantum mechanical principles and phenomena as a basis for implementation in sensing (atomic resonances, superconducting Josephson effect, population inversion...)
• Quantum sensing based on first generation quantum technologies (laser systems, clocks, MRI, current standards, photonic systems, interferometry, laser cooling, LIGO, quantum dots, squeezed states...).
• Quantum sensing based on first generation quantum technologies (atom optics, cold atoms, Bose-Einstein condensates, entanglement, NV centers,...).
• Atomic Clocks, Quantum Radar, Magnetometers, Inertial Sensors, Quantum Gravity Gadiometers,...
• Engineering prerequisites for the use of specific phenomena with respect to the feasibility of quantum sensing measurement systems: e.g. by the use of auxiliary technologies, such as vacuum technology, microsystem technology, laser system technology.

Literature
F. Schwabl: Quantenmechanik und Quantenmechanik für Fortgeschrittene
T.Fließbach: Quantenmechanik
W. Nawrocki: Introduction to Quantum Metrology
E.Goebel, U. Siegner: Quantum Metrology, Foundation of Units and Measurement
I.Djodjevic: Quantum Communication, Quantum Networks and Quantum Sensing

Recent publications and articles

Lecture notes and slides

Teaching and learning methods
Lecture, 2 SWS
Workload

30 h lecture (attendance)
90 h self study
Total: 120 h

Assessment

The module examination consists of a graded written or oral examination, depending on the number of participants. If a specified academic work is achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

Grading procedure

The module grade is equal to the examination grade.

Basis for

Quantum Sensing II
# Quantum Sensing II

Modules referring to Quantum Physics

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<td>Duration</td>
<td>1</td>
</tr>
<tr>
<td>Cycle</td>
<td>each Summer Semester</td>
</tr>
</tbody>
</table>
| Coordinator               | Prof. Dr. Claus Brixmaier  
                            | Lee Kumanchik Ph.D. |
| Instructor(s)             | Lee Kumanchik Ph.D. |

**Allocation of study programmes**
- Communications and Computer Engineering M.Sc.
- Electrical Engineering M.Sc.
- Quantum Engineering M.Sc.
- Communication and Information Technology M.Sc.
- Sensorsystemtechnik M.Sc.
- Physics M.Sc.

**Recommended prerequisites**
- Contents of basic physics (e.g. Physics for Engineers module) incl. basics of photonics.
- Quantum Sensing I

**Learning objectives**
Students who have successfully completed this module,
- have a detailed understanding of the operating principle of quantum sensors,
- know experimental techniques and technologies to realize and control quantum states in quantum sensing instruments,
- know how to apply noise models to calculate sensor performance and make predictions,
- know how to experimentally measure and analyze the intrinsic noise of sensors,
• can learn the basic principles of back-action evading measurements,
• know the techniques for decoupling quantum sensors from the environment, for example, using vacuum systems, thermal shielding, etc.
• know how to implement controllers/servos for environmental stabilization,
• know how to model material behavior with respect to temperature changes,
• know how to model the optical field using various passive and active optical elements commonly found in quantum sensors,
• know how to design optical plug-in boards for quantum sensors,
• can work at the interface between physics and engineering,
• independently deepen their knowledge in the field of quantum sensing and gain strategies for literature review.

Syllabus
In this lecture, the following technical content will be taught:

• Different actual quantum sensors: Atomic/molecular clocks, frequency references, quantum inertial sensors, quantum gravity gradiometers, LIGO,
• Laser servos, temperature controllers, platform stabilizers,
• Noise sources and their origins: electronic noise, optical noise, pressure noise, thermal noise, etc.
• Optical field propagation through linear and nonlinear media,
• Measurement by frequency mixing techniques,
• Optomechanical feedback and optical cavities (cavities),
• Material response to temperature changes and dilatometry,
• Engineering technologies for quantum systems: vacuum technology, detector technology, thermal management, etc.

Literature
F. Schwabl: Quantenmechanik und Quantenmechanik für Fortgeschrittene
T.Fließbach: Quantenmechanik
W.Nawrocki: Introduction to Quantum Metrology
E.Goebel, U.Siegner: Quantum Metrology, Foundation of Units and Measurement
IDjodjevic: Quantum Communication, Quantum Networks and Quantum Sensing

Recent publications and Articles

Lecture notes and slides

Teaching and learning methods
Lecture 2 SWS

Workload
30 h lecture (attendance)
90 h self-study
Total: 120 h

Assessment
The module examination consists of a graded written or oral examination, depending on the number of participants. If a specified academic work is
achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

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<tr>
<td>Basis for</td>
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</table>
Quantum theory of macroscopic mechanical systems
Modules referring to Quantum Physics

Code 8802877110
ECTS credits 6
Attendance time 5
Language of instruction English or German
Duration 1
Cycle each Summer Semester
Coordinator Dean of Physics Studies
Instructor(s) Prof. Dr. Benjamin Stickler

Allocation of study programmes
Physics M.Sc., elective module
Quantum Engineering M.Sc., elective module

Recommended prerequisites Quantum mechanics

Learning objectives Students who successfully passed this module:
• understand how to quantize electromagnetic radiation in the presence of atoms and dielectric media.
• know how to solve problems involving the quantum mechanical motion of complex systems.
• understand quantum technologies and fundamental tests based on mechanical degrees of freedom.

Syllabus The following technical contents are taught in this module:
Field quantization in presence of dielectric matter
• Canonical Quantization of the EM field
• Light-matter interaction
• Field quantization in dielectrics

Molecular matter-wave interference
• Molecule light interaction
• Eikonal diffraction
• Far-field vs near-field interference
Cavity optomechanics

- Optomechanical Hamiltonian & cooling
- Sensing at the standard quantum limit
- Levitated nanoparticles
- Fundamental tests and sensing applications

Heating and decoherence in macroscopic quantum systems

- Monitoring master equation
- Quantum Langevin equations
- Collisional decoherence and momentum diffusion

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<th>Literature</th>
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<tr>
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<td>Exercise 2 classroom hours</td>
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<tr>
<th>Workload</th>
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<td></td>
<td>30 hours exercise (attendance time)</td>
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<td></td>
<td>105 hours private study</td>
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| Assessment | The module examination consists of a graded written or oral examination, depending on the number of participants. Participation in the examination requires an ungraded study achievement. The type, content and scope of the study achievement[s] will be announced in good time in the course information and the course catalogue. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date. |

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# Seminar Quantum Sensing and Metrology

Modules referring to Quantum Physics

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<td>Cycle</td>
<td>each Winter Semester</td>
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<tr>
<td>Coordinator</td>
<td>Dean of Physics Studies</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>Prof. Dr. Fedor Jelezko, Prof. Dr. Peter Reineker</td>
</tr>
</tbody>
</table>
| Allocation of study programmes | Physics M.Sc., elective module, 1st or 2nd semester  
Wirtschaftsphysik M.Sc., elective module, 1st - 3rd semester |
| Recommended prerequisites | Fundamentals of classical mechanics and atomic physics |
| Learning objectives | Students who successfully passed this module are able to start research in quantum sensing and have an overview over the actual SI unit system. |
| Syllabus |  
* Quantum sensing, several methods  
* Metrology, several methods  
* Overview over basic quantum sensing methods  
* Overview over the SI unit system (update in May 2019) |
| Literature | - |
| Teaching and learning methods | Seminar (2 hours per week) |
| Workload | 30 hours seminar (attendance time)  
60 hours talk preparation  
Total: 90 hours |
Assessment

The award of the credit points for this module is based on completion of an assignment. The colloquium and the participation in the discussion will be graded. At the beginning of the seminar the topics will be assigned and the examination details will be announced. No prerequisites are necessary for exam registration.

Grading procedure

The module grade is equal to the examination grade.

Basis for

Research in the field of quantum sensing, experiment and/or theory
Seminar Ultracold Quantum Gases
Modules referring to Quantum Physics

Code 8802875024

ECTS credits 3

Attendance time 2

Language of instruction English

Duration 1

Cycle each Winter Semester

Coordinator Dean of Physics Studies

Instructor(s) Prof. Dr. Johannes Hecker Denschlag

Allocation of study programmes Physics M.Sc., elective module Wirtschaftsphysik M.Sc., elective module

Recommended prerequisites Profound knowledge in atomic physics and quantum mechanics.

Learning objectives The seminar addresses both fundamental and advanced topics in the fascinating field of ultracold quantum gases. The talks are based on a small number of selected publications and are intended to provide a good understanding of the underlying physics. Enough time is arranged for relaxed and stimulating discussions in order to deepen the acquired knowledge.

Syllabus

1. Matter-wave interferometry and gravitational measurements
2. Nonlinear atom optics, 4-wave mixing, and solitons
3. Scattering length and Feshbach resonance
4. Optical lattices and Hubbard model
5. Ultracold molecules
6. Repulsively bound atom pairs
7. Ultracold Fermi gases
8. Quantum cradle
9. Quantum walk
10. Rydberg atoms

Literature -
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<th><strong>Teaching and learning methods</strong></th>
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<td><strong>Workload</strong></td>
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<td><strong>Assessment</strong></td>
<td>The module examination consists of completing an assignment on a given topic and a graded oral presentation of the results as well as participating in the discussion.</td>
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### Theoretical Quantum Optics

- **Modules referring to Quantum Physics**

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<td>Duration</td>
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<tr>
<td>Cycle</td>
<td>each Summer Semester</td>
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<tr>
<td>Coordinator</td>
<td>Dean of Physics Studies</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>Prof. Martin B. Plenio, Dr. Jaemin Lim</td>
</tr>
</tbody>
</table>

#### Allocation of study programmes
- Physics M.Sc., elective module, 1<sup>st</sup> or 2<sup>nd</sup> semester

#### Recommended prerequisites
- Non-relativistic Quantum Mechanics, classical Electrodynamics, Thermodynamics and Statistics

#### Learning objectives
- Students who have taken this course
  - are familiar with the concepts of theoretical quantum optics
  - are able to transfer their knowledge to other branches of physics.

#### Syllabus
- Quantum phase space distributions, and in particular, the Wigner function
- Tools of semi-classical quantum mechanics
- Wave packet dynamics and connections to number theory
- Quantization of the radiation field
- Interaction Hamiltonian of light and matter
- Jaynes-Cummings model
- Atom optics with classical and quantized light fields

#### Literature
- W.P. Schleich, Quantum Optics in Phase Space (Wiley-VCH, Weinheim, 2001)
- M.O. Scully and M.S. Zubairy, Quantum Optics (Cambridge University Press, Cambridge, 1997)
**Teaching and learning methods**
- Lecture (3 hours per week)
- Exercise (2 hours per week)

**Workload**
- 45 hours lecture (attendance time)
- 30 hours exercise (attendance time)
- 105 hours self-study and exam preparation
- Total: 180 hours

**Assessment**
The module examination consists of a graded written or oral examination, depending on the number of participants. Participation in the examination requires an ungraded study achievement. If a specified academic work is achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The type, content and scope of the study achievement[s] will be announced in good time in the course information and the course catalogue. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

**Grading procedure**
The module grade is equal to the examination grade.

**Basis for**
Research in the fields of Quantum Information and Technologies
Theory of Quantum Information
Modules referring to Quantum Physics

Code 8802871500

ECTS credits 6

Attendance time 5

Language of instruction English

Duration 1

Cycle each Winter Semester

Coordinator Dean of Physics Studies

Instructor(s) Prof. Martin Plenio

Allocation of study programmes
- Physics M.Sc., elective module
- Physik B.Sc., elective module
- Wirtschaftsphysik M.Sc., elective module

Recommended prerequisites
- Foundations of quantum mechanics

Learning objectives
- Students who successfully pass this module
  - are familiar with the theoretical concepts of Quantum Information
  - know the application of Quantum Information to other areas of physics, such as quantum mechanical many-particle systems, statistical physics and computer sciences.

Syllabus
- What is Quantum Information Processing?
- Quantum complexity and quantum parallelism
- Decoherence and errors in a quantum computer
- Quantum bits, quantum gates, quantum circuits
- Quantum circuits for entanglement production, teleportation, error correction
- Quantum dynamics and measurement processes
- Ensembles of quantum states and density operators
- EPR paradox and Bell inequalities
- Quantum cryptography
- Quantum algorithms
- Physical realizations of quantum processors
Literature

- Preskill, Quantum Computation Lecture Notes

Teaching and learning methods

Lecture (3 hours per week)
Tutorials (2 hours per week)

Workload

45 hours lecture (attendance time)
30 hours tutorials (attendance time)
105 hours self-study and exam preparation
Total: 180 hours

Assessment

The module examination consists of a graded written or oral examination, depending on the number of participants. Participation in the examination requires an ungraded study achievement. If a specified academic work is achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The type, content and scope of the study achievement[s] will be announced in good time in the course information and the course catalogue. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

Grading procedure

The module grade is equal to the examination grade.

Basis for

Research in the fields of quantum information and technologies
Ultracold Quantum Gases
Modules referring to Quantum Physics

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<td>Cycle</td>
<td>each Summer Semester</td>
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<tr>
<td>Coordinator</td>
<td>Dean of Physics Studies</td>
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<tr>
<td>Instructor(s)</td>
<td>Prof. Johannes Hecker Denschlag</td>
</tr>
<tr>
<td>Allocation of study programmes</td>
<td>Physics M.Sc., elective module, 1st or 2nd semester</td>
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Recommended prerequisites
Fundamentals of quantum mechanics

Learning objectives
Students who have successfully completed this module
- have in-depth knowledge of quantum physics
- know experimental methods for the investigation of gases at very low temperatures
- understand the quantum-physical properties of extremely cold fermionic and bosonic gases

Syllabus
- Laser cooling
- Atomic and molecular traps
- Ultra-cold collisions
- Bose-Einstein condensation
- Degenerate Fermi gases
- Matter-wave interferometry
- Superfluidity
- Artificial solids with optical lattices
- Non-linear dynamics with cold atoms
- Quantum mechanical entanglement of atoms
Literature -

Teaching and learning methods

- Lecture (3 hours per week)
- Tutorials (2 hours per week)

Workload

- 45 hours lecture (attendance time)
- 30 hours tutorials (attendance time)
- 105 hours self-study and exam preparation
- Total: 180 hours

Assessment

The module examination consists of a graded written or oral examination, depending on the number of participants. Participation in the examination requires an ungraded study achievement. If a specified academic work is achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The type, content and scope of the study achievement[s] will be announced in good time in the course information and the course catalogue. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

Grading procedure

The module grade is equal to the examination grade.

Basis for

Research in the fields of quantum information and technologies
Advanced Quantum Engineering
Modules referring to Electrical Engineering

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<td>Cycle</td>
<td>each Winter Semester</td>
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<tr>
<td>Coordinator</td>
<td>Prof. Claus Braxmaier</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>Dr. Lisa Wörner</td>
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**Allocation of study programmes**
- Electrical Engineering and Information Technology M.Sc.
- Communications and Computer Engineering M.Sc.
- Communication and Information Technology M.Sc.

**Recommended prerequisites**
- Solid Basics in Physics (for instance: Modul Physik für Ingenieure)
- Lecture: Introduction to Quantum Engineering

**Learning objectives**
- Students, that have completed this module successfully,
  - Have an overview over basic quantum mechanical phenomena
  - Know about the applications of quantum mechanical phenomena, i.e. for sensing, material research, communication, and computing
  - Have an overview over quantum technologies
  - Know about current developments in quantum engineering and supporting technologies, i.e. vacuum systems, laser technologies, metrology, microsystems, and materials
  - Know the basics of technology development and market evaluation
  - Are able to judge specific challenges
  - Can develop solutions to complex engineering challenges
  - Have strategies to transfer technology to industry
  - Can work at the interface between physics and engineering
  - Widen independently their knowledge in quantum technologies and have strategies for efficient literature search

**Syllabus**
In this lecture the following content will be taught:
• Overview over current systems in the area of quantum engineering: i.e. quantum optical frequency references for time metrology, bose-einstein condensation, matter-wave interferometer, quantum sensors for magnetic field and inertial sensing, quantum entanglement systems for communication and computing
• Market related potentials and risks of quantum technologies
• Technology developments: i.e.: Miniaturization, Lab-on-the-chip, requirements towards fabrication, performance and environmental test strategies
• Current Challenges in Technology, TRL, and technology transfer: i.e. Explanation of TRL, open questions of implementation and realization, strategies for addressing and solving open issues, industrial challenges, requirements management.

**Literature**

F. Schwabl: Quantum Mechanics and Advanced Quantum Mechanics
T. Fließbach: Quantenmechanik
I.V. Hertel, C.-P. Schulz, Atome Moleküle und optische Physik
W. Demtröder, Experimentalphysik 3
A.M. Zagoskin, Quantum Engineering
NASA Systems Engineering Handbook Rev. 2
Current Publications and articles
Script and Slides from the lecture

**Teaching and learning methods**

Lecture Advanced Quantum Engineering: 2 SWS

**Workload**

30 h Lecture
90 h Self-study and preparation for the exam
Total: 120 h

**Assessment**

The module examination consists of a graded written or oral examination, depending on the number of participants. If a specified academic work is achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

**Grading procedure**

The grade of the module will be the grade of the exam.

**Basis for**

-
Applied Information Theory
Modules referring to Electrical Engineering

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<tr>
<td>Coordinator</td>
<td>Prof. Dr. Robert Fischer</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>Prof. Dr. Robert Fischer</td>
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Allocation of study programmes
- Electrical Engineering and Information Technology, M.Sc., Elective Module, Engineering Sciences
- Electrical Engineering and Information Technology, M.Sc., Elective Module, Communication and System Technology
- Electrical Engineering and Information Technology, M.Sc., Optional Module, Automation and Energy Technology
- Communications and Computer Engineering, M.Sc., Elective Module, Communications Technology, M.Sc., Optional Module, Communications Circuits and Systems
- Communications Technology, M.Sc., Compulsory Module, Communications Engineering
- Computer Science, M.Sc., Specialization Subject, Informationstheorie

Recommended prerequisites
- Bachelor
- Probability theory

Learning objectives
Information theory provides a measure for information and describes fundamental limits for communication and storage systems with respect to source coding, channel coding, multi-user communication, and cryptology. The students will be able to explain, apply and analyze lossless and lossy source coding algorithms (data compression). Furthermore, they will be able to evaluate the performance with respect to the source coding theorem which states that Shannons uncertainty is the fundamental limit for compression. They can describe and analyze the channel capacity as the fundamental limit of information which can be transmitted error free over a channel using an appropriate code with a certain
rate. With this context they can categorize and evaluate channels and transmission methods. For the omnipresent Gaussian noise the channel capacity can be calculated and interpreted.

For basic multi-user communication scenarios (broadcast and multiple access) fundamental algorithms (Tomlinson-Harashima, superposition coding, etc.) and their application can be analyzed and evaluated based on the mutual information. These algorithms and methods enable the students to analyze and categorize also scenarios which are not treated in the module or will be developed in the future.

The information theoretic point-of-view of cryptology enables the students to compare, categorize, and evaluate crypto algorithms.

Syllabus

Information theory is the basis of modern telecommunication systems. Main topics of information theory are source coding, channel coding, multi-user communication systems, and cryptology. These topics are based on Shannon's work on information theory, which allows to describe information with measures like entropy and redundancy. After a short overview of the whole area of information theory, we consider concepts for statistical modeling of information sources and derive the source coding theorem. Afterwards, important source coding algorithms like Huffman, Tunstall, Lempel-Ziv and Elias-Willers are described.

The second part of the lecture investigates channel coding. Important properties of codes and fundamental decoding strategies are explained. Moreover, we introduce possibilities for estimating the error probability and analyze the most important channel models according to the channel capacity introduced by Shannon. The Gaussian channel is very important, and therefore, described extensively. The third part deals with aspects of multi-user communication systems.

We introduce several models and investigate methods that can achieve the capacity regions. Finally, we give an introduction on data encryption and secure communication. In the projects, several information theoretic topics (e.g., Lempel-Ziv-coding) will be investigated by means of implementation tasks.

Overview: Basics:
- Uncertainty (entropy), mutual information
- Fanos lemma, data processing lemma, information theory inequality

Source Coding:
- Shannon's source coding theorem
- Coding methods for memoryless sources: Shannon-Fano-, Huffman-, Tunstall, and arithmetic coding
- Coding for sources with memory

Channel Coding:
- Concepts of linear binary block codes
- Shannon's channel coding theorem
- Random coding and error exponent
- MAP (maximum a-posteriori) and ML (maximum likelihood) decoding
- Bounds (Bhattacharriyya, union, etc.)
- Channels and capacities: Gaussian channel, fading channel

Multi-User Systems:
- Duplex transmission
- MAC (multiple access) channel
- BC (broadcast) channel
- MIMO (multiple input multiple output) channel

Cryptology:
- Problem settings in cryptology
- IT-security

Projects: Universal Source Coding (Lempel-Ziv-coding) and Mutual Information
### Literature
- Cover, Thomas: Elements of Information Theory, Wiley
- Script 2009 (in German)
- Johannesson: Informationstheorie - Grundlagen der (Tele-) Kommunikation, Addison-Wesley

### Teaching and learning methods
- Lecture “Applied Information Theory”, 3 SWS
- Exercise “Applied Information Theory”, 2 SWS
- Project “Applied Information Theory”, 1 SWS

### Workload
- Active Time: 90 h
- Preparation and Evaluation: 150 h
- Sum: 240 h

### Assessment
- The module examination consists of a graded written or oral examination, depending on the number of participants. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

### Grading procedure
- The module grade is equal to the examination grade.

### Basis for
- Communication Engineering and Wireless
# Laboratory Semiconductor Technology

Modules referring to Electrical Engineering

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<td>Duration</td>
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<td>Cycle</td>
<td>Each Summer Semester</td>
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<tr>
<td>Coordinator</td>
<td>Prof. Dr.-Ing. Peter Unger</td>
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<tr>
<td>Instructor(s)</td>
<td>Prof. Dr.-Ing. Peter Unger</td>
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<tr>
<td>Allocation of study programs</td>
<td>Electrical Engineering and Information Technology, M.Sc., Elective Module Communications Technology, M.Sc., Optional Lab Course, Communications Circuits and Systems</td>
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<tr>
<td>Recommended prerequisites</td>
<td>Lecture &quot;Semiconductor Technology&quot; or &quot;Modern Semiconductor Devices&quot;</td>
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<tr>
<td>Learning objectives</td>
<td>Students discover how to work under clean-room conditions, recognizing how different technology steps may be combined to produce electron devices. Furthermore, they practice to operate complex semiconductor-technology equipment. Participants modify the surface of semiconductor wafers employing thermal evaporation of different metals like Aluminum and Gold. They create microstructured contacts by photo-lithography. Test structures, diodes, and transistors are evaluated using fundamental current-voltage and capacitance-voltage measurements. The students evaluate the influence of scaling parameters (geometry, size) on the electrical behaviour of the devices (output- and transfer-characteristics).</td>
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<tr>
<td>Syllabus</td>
<td>Aim of this lab course is the fabrication of field-effect-transistors (GaAs-MESFET's) and their electrical characterization. The lab course takes place in a cleanroom facility specifically equipped for education. Main focuses this lab course are: - deposition of metals by evaporation</td>
</tr>
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- patterning of contacts by optical lithography
- patterning of contacts by wet etching
- manufacturing of ohmic- and Schottky contacts
- electrical characterization of the fabricated devices

**Literature**

**Teaching and learning methods**
Labor “Semiconductor Technology”, 4 SWS

**Workload**
- Active Time: 28 h
- Preparation and Evaluation: 122 h
- Sum: 150 h

**Assessment**
The module examination consists of an ungraded participation in all phases of the laboratory course. The evaluation scheme will be announced at the beginning of the lab.

**Grading procedure**
The module is not graded.

**Basis for**
Master's Thesis
Integrated Broadband Circuits
Modules referring to Electrical Engineering

Code 8802875196

ECTS credits 6

Attendance time 4

Language of instruction English

Duration 1

Cycle each Winter Semester

Coordinator Prof. Dr.-Ing. habil. Dietmar Kissinger

Instructor(s) Prof. Dr.-Ing. habil. Dietmar Kissinger

Allocation of study programmes
- Master Electrical Engineering and Information Technology > Vertiefungsmodul
- Master Informationssystemtechnik > Vertiefungsmodul
- Master Communications Technology > Vertiefungsmodul > Communications Engineering
- Master Communications Technology > Vertiefungsmodul > Communications Circuits and Systems

Recommended prerequisites Basic knowledge of semiconductor devices, analog circuits, and microwave engineering.

Learning objectives Students recognize fundamental requirements of wireline and fiberoptic communication systems. They review and analyze important broadband transmitter and receiver frontend circuit topologies and identify those suitable. They then synthesize circuits to meet the specifications of selected examples, assess their performance using computer aided design tools, and compare the results obtained with the initial system requirements.

Syllabus
- Broadband amplifiers
- Laser and modulator drivers
- Transimpedance amplifiers
- High-speed logic
- RF DACs and ADCs
- PLLs and CDR

<table>
<thead>
<tr>
<th>Literature</th>
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<tbody>
<tr>
<td>E. Säckinger, Broadband Circuits for Optical Fiber Communication, Wiley, 2005</td>
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<tr>
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<td>Classroom hours (3 SWS)</td>
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<tr>
<td>Exercise courses (1 SWS)</td>
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<td>Exercise: 14h</td>
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<td>Self-Study: 60h</td>
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| Assessment | The module examination consists of a graded oral examination. |
| Grading procedure | The module grade is equal to the examination grade. |
| Basis for | Master thesis at the Institute of Electronic Devices and Circuits. |
**Integrated High-Frequency Circuits**
Modules referring to Electrical Engineering

**Code** 8802875166

**ECTS credits** 6

**Attendance time** 4

**Language of instruction** English

**Duration** 1

**Cycle** each Summer Semester

**Coordinator** Prof. Dr.-Ing. habil. Dietmar Kissinger

**Instructor(s)** Prof. Dr.-Ing. habil. Dietmar Kissinger

**Allocation of study programmes**
- Master Electrical Engineering and Information Technology
- Master Communication and Information Technology.

**Recommended prerequisites** Basic knowledge of semiconductor devices, analog circuits, and microwave engineering.

**Learning objectives** Students recognize fundamental requirements of microwave and millimeter-wave communication and sensing systems. They review and analyze important high-frequency frontend circuit topologies and identify those suitable. They then synthesize circuits to meet the specifications of selected examples, assess their performance using computer aided design tools, and compare the results obtained with the initial system requirements.

**Syllabus**
- Passive integrated elements
- Low-noise and power amplifiers
- Mixers and frequency multipliers
- Oscillators
- Baluns and quadrature generation
- Transmitters and receivers

**Literature**
- S. Prasad, H. Schumacher, A. Gopinath, „High-Speed Electronics and Optoelectronics”, Cambridge University Press
- S. P. Voinigescu, „High-Frequency Integrated Circuits“, Cambridge University Press
- B. Razavi, „RF Microelectronics“, Prentice Hall

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| Assessment                    | The module examination consists of a graded oral examination. |

| Grading procedure             | The module grade is equal to the examination grade. |

<table>
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<tr>
<th>Basis for</th>
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**Integrated Interface Circuits**

Modules referring to Electrical Engineering

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<tr>
<td>Coordinator</td>
<td>Prof. Dr.-Ing Maurits Ortmanns</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>Prof. Dr.-Ing Maurits Ortmanns</td>
</tr>
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**Allocation of study programmes**

Electrical Engineering and Information Technology, M.Sc., Elective Module
Communications Technology, M.Sc., Optional Technical Module, Communications Circuits and Systems

**Recommended prerequisites**

Successful participation in the course "Integrated Analog Circuits" or a similar qualification are recommended for a successful course participation.

**Learning objectives**

The students can identify the most relevant noise sources in sensors and sensor readout electronics and predict their effect on the achievable signal noise ratios. They can distinguish various sensor and transducer principles and apply appropriate readout electronic circuits. The students can differentiate open-loop and closed-loop readout concepts and apply concepts for offset and noise-reduction.

The students analyze and compare different A/D and D/A converter structures concerning their achievable specifications. The students can explain the concept of discrete-time and continuous-time noise-shaping Sigma-delta ADCs and of charge redistribution SAR ADC, as well as the concept of time-to-digital conversion.

The students are able to distinguish various biosignals and give an overview of implantable system requirements. The students can analyze circuit architectures for biosignal recording and neurostimulation circuits. The students identify the problems associated with residual stimulation charge and apply various methods for charge balancing.
The students analyze a research paper in the field of integrated interface circuits and give a presentation on the same.

**Syllabus**

1. Motivation and example sensor Applications
2. Sensors and Sensor Interface Circuits
   a. Noise in sensor interface circuits
   b. Transducers
   c. Bandgap references and integrated temperature sensors
   d. Resistive and inductive readouts circuits
   e. Capacitive readouts circuits, open and closed loop concepts, force feedback
   f. Autozeroing, Chopping, Correlated Double Sampling
3. Analog/Digital Interfaces
   a. Quantization and Sampling
   b. Spectral Metrics
   c. DAC overview
   d. Nyquist and oversampling DACs
   e. ADC overview
   f. Comparators
   g. SAR ADC
   h. Oversampling (Sigma-Delta) ADC
   i. Time-to-digital converts
4. Biomedical Interface Circuits
   a. Excitable cells and biosignals
   b. Overview on microelectrodes, biocompatibility, packaging
   c. Telemetry and inductive powering
   d. Neural recording, stimulation and modulation circuits and systems
   e. Charge Balancing Strategies
   f. Applications: Cardiac devices, Neuromuscular simulators, Gastrointestinal devices and obesity treatment, Drug delivery devices and infusion pumps, Diabetes treatment, Rehabilitation Engineering
   g. Examples for implantable biosensors

**Literature**

Teaching and learning methods
- Integrated Interface Circuits (L), 3 SWS
- Integrated Interface Circuits (S), 1 SWS

Workload
- Lecture: Attendance: 42 h
- Lecture review: 28 h
- Seminar preparation: 16 h
- Preparation of the oral presentation and written documentation: 44 h
- Exam preparation and exam participation: 50 h
- Total: 180 h

Assessment
The module examination consists of a graded oral examination. Participation in the examination requires an ungraded study achievement. The type, content and scope of the study achievement[s] will be announced in good time in the course information and the course catalogue.

Grading procedure
The module grade is equal to the examination grade.

Basis for
Master-Thesis
Microwave System Design
Modules referring to Electrical Engineering

Code 8802875197

ECTS credits 6

Attendance time 4

Language of instruction English

Duration 1

Cycle each Winter Semester

Coordinator Dr.-Ing. Christian Waldschmidt

Instructor(s) Dr.-Ing. Christian Waldschmidt
Dr.-Ing. Christian Damm
Dr.-Ing. Frank Bögelsack

Allocation of study programmes
Electrical Engineering and Information Technology, M.Sc.
Comunications and Computer Engineering, M.Sc.
Communication Technology, M.Sc.

Recommended prerequisites Module "Introduction to Microwave Engineering"

Learning objectives After successful completion of this module, students are able to describe electromagnetic waves on transmission lines and passive components. They are able to analyse fundamental properties of mixers and oscillators, in particular under consideration of the non-linear behavior and phase noise. After successful completion of this module, they are able to design and to characterize experimentally RF systems for communications and sensing. They are able to assess the advantages and disadvantages of different transmit and receive systems and subsystems. They can determine the noise and power budget of a transmit receive system, allowing them to do own design work. The students are able to name the special problems which can occur and the calibration procedures in measuring RF components. The focus is on measuring the scattering parameters of two-ports and the spectral analysis.

Syllabus This lecture introduces students into various aspects of radio communications. Wireless communication and sensing systems are decomposed into subsystems as transmitters, radio channels, and receivers. These systems are systematically...
analyzed and subdivided into further subsystems. The objective of this lecture is to mediate all necessary tools for successfully analyzing existing radio-communication systems, and for designing new ones. The lecture covers in particular system aspects of:

- transmission line types and passive components,
- frequency conversion, mixers,
- oscillators and PLL,
- mixer noise and phase noise,
- large signal behavior and intermodulation,
- amplifiers (small and large signal behavior),
- design principles and architectures for receivers, transmitters,
- power link budgets,
- RF measurement techniques with focus on network and spectral analysis.

**Literature**
- skript: Lecture handout
- Text books: see lecture handout

**Teaching and learning methods**
- Lecture: Microwave System Design
- Exercise: Microwave System Design

**Workload**
- Lecture Time: 60 h
- Preparation: 60 h
- Selfstudy: 60 h
- Sum: 180 h

**Assessment**
The module examination consists of a graded written or oral examination, depending on the number of participants.

**Grading procedure**
The module grade is equal to the examination grade.

**Basis for**
-
## Optical Communications
Modules referring to Electrical Engineering

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<td>Cycle</td>
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<tr>
<td>Coordinator</td>
<td>apl. Prof. Dr.-Ing. habil. Rainer Michalzik</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>apl. Prof. Dr.-Ing. habil. Rainer Michalzik</td>
</tr>
</tbody>
</table>

### Allocation of study programmes
- Electrical Engineering and Information Technology, M.Sc., Elective Module
- Communications Technology, M.Sc., Compulsory Elective Module, Track Communications Engineering
- Communications Technology, M.Sc., Compulsory Module, Track Communications Circuits and Systems

### Recommended prerequisites
Bachelor. No prerequisites from other modules required. Some basic knowledge of semiconductor physics and devices would be helpful

### Learning objectives
The students are able to summarize the benefits of optical versus electrical data transmission. They can employ a ray-optical model to describe the light propagation in optical waveguides and can identify situations where a wave-optical model is needed. The students can name and sketch different kinds of optical fibers as well as discuss the associated dispersion mechanisms which lead to bandwidth limitations. Origins of loss in optical fibers can be listed and fiber fabrication be outlined. They can state boundary conditions of field variables to formulate characteristic equations for waveguide problems. The students can describe the structure of common semiconductor crystals as well as the composition dependence of parameters required to model the wave propagation. Appropriate semiconductor material systems for particular applications can be selected and interband transition mechanisms be sketched. They are able to explain the operation of a light emitting diode and rate their use in fiber-based optical communication systems. The students can illustrate the function of a laser diode and name the contributions to the laser rate equations. They master to solve the rate equations for static and dynamic operating conditions. The students can discuss the role of a pn-junction for light detection. Factors influencing the efficiency and the bandwidth of a photodiode can be pointed out. They can relate
the current noise in a photoreceiver to the measured bit error ratio of a digital optical communication link. The optical power budget can be calculated. The students are able to list and discuss multiplexing techniques for increasing the data throughput of an optical communication system. The basic function of optical (de-)multiplexing devices can be stated. They can moreover sketch the building blocks of an optical repeater and explain the operation of an optical fiber amplifier.

### Syllabus

This module provides a solid basis for understanding fiber-optic data transmission systems. Important components like the silica optical fiber as transmission medium, light emitting diode or laser diode transmitters, optical amplifiers, as well as photodiode receivers are discussed in some detail. The entire system is characterized in terms of its bit error ratio performance and its power budget. The following topics are addressed:

- Properties of optical communication systems
- Optical fibers: ray-optical model, step-index and graded-index fibers, wave-optical model, chromatic dispersion
- Wave propagation in planar waveguides
- Loss in optical fibers: absorption and scattering
- Fabrication of fibers
- Semiconductor materials: crystal lattices, direct and indirect bandgaps, mixed compound semiconductors, absorption and refractive index, emission and absorption
- Light-emitting diodes for communications
- Laser diodes
- Photodiodes
- Optical communication systems: detection sensitivity for digital signals, optical power budget
- Signal multiplexing: electrical time division multiplexing (ETDM), dense and coarse wavelength division multiplexing (WDM), optical (de-)multiplexing devices, space division multiplexing (SDM)
- Signal restoration: electronic repeater, erbium-doped fiber amplifier (EDFA), alternative optical amplifiers
- Laser diodes
- Photodiodes
- Optical communication systems: detection sensitivity for digital signals, optical power budget
- Signal multiplexing: electrical time division multiplexing (ETDM), dense and coarse wavelength division multiplexing (WDM), optical (de-)multiplexing devices, space division multiplexing (SDM)
- Signal restoration: electronic repeater, erbium-doped fiber amplifier (EDFA), alternative optical amplifiers

### Literature

A comprehensive English written manuscript is provided.

### Teaching and learning methods

Lecture “Optical Communications”, 3 hours per week
Exercise “Optical Communications”, 1 hours per week

### Workload

Preparation and Evaluation: 56 h
Active Time: 49 h
Self-Study: 75 h
Sum: 180 h
<table>
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<th>The module examination consists of a graded written or oral examination, depending on the number of participants. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.</th>
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<tr>
<td>Grading procedure</td>
<td>The module grade is equal to the examination grade.</td>
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<tr>
<td>Basis for</td>
<td>Advanced Optoelectronic Communication Systems, Active Optoelectronic Devices</td>
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### Quantum Sensing I
Modules referring to Electrical Engineering

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<td>Cycle</td>
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</table>
| Coordinator         | Prof. Dr. Claus Braxmaier  
                      | Lee Kumanchik, Ph.D. |
| Instructor(s)       | Lee Kumanchik, Ph.D. |
| Allocation of study programmes |
| Communications and Computer Engineering M.Sc. |
| Electrical Engineering M.Sc. |
| Quantum Engineering M.Sc. |
| Communication and Information Technology M.Sc. |
| Sensorsystemtechnik M.Sc. |
| Physics M.Sc. |

### Recommended prerequisites
Contents of basic physics (e.g. Physics for Engineers module) incl. basics of photonics

### Learning objectives
Students who have successfully completed this module,

- have an overview of basic quantum mechanical principles
- know the applications of quantum mechanical phenomena for sensor technology and also for communication and computer technology
- know qualitatively and quantitatively the interaction of quantum states with the environment and know about the higher sensitivity of this and traceability to Planck's constant
- have a rough overview of current quantum technologies
- have a basic knowledge of measurement techniques including statistical methods of data acquisition, analysis and presentation
• know about the advantages of using quantum sensors in general and in particular to achieve the standard quantum limit and below,
• know the wide range of measurands, such as acceleration, temperature, magnetic field, electric field, pressure, frequency, time, pH, concentration....
• know about the achievable accuracy and sensitivity of the respective method, as well as the interferences on the respective measurement systems
• know the fields of application of quantum sensors in technology, physics, biology, medicine, aerospace and mobility
• know basic methods of microsystems engineering for the development of miniaturized quantum sensors up to lab-on-a-chip.
• are able to work at the interface between physics and engineering science
• independently expand their knowledge in the field of quantum sensor technology and are provided with strategies for literature searches

Syllabus
In this lecture the following technical contents will be taught:
• highest resolution sensing and metrology needs: engineering, physics, biology, medicine, aerospace and mobility.
• Fundamentals of sensor technology, overview of sensory systems and metrology
• fundamental quantum mechanical principles and phenomena as a basis for implementation in sensing (atomic resonances, superconducting Josephson effect, population inversion...)
• Quantum sensing based on first generation quantum technologies (laser systems, clocks, MRI, current standards, photonic systems, interferometry, laser cooling, LIGO, quantum dots, squeezed states...).
• Quantum sensing based on first generation quantum technologies (atom optics, cold atoms, Bose-Einstein condensates, entanglement, NV centers,...).
• Atomic Clocks, Quantum Radar, Magnetometers, Inertial Sensors, Quantum Gravity Gadiometers,...
• Engineering prerequisites for the use of specific phenomena with respect to the feasibility of quantum sensing measurement systems: e.g. by the use of auxiliary technologies, such as vacuum technology, microsystem technology, laser system technology.

Literature
F. Schwabl: Quantenmechanik und Quantenmechanik für Fortgeschrittene
T.Fließbach: Quantenmechanik
W. Nawrocki: Introduction to Quantum Metrology
E.Goebel, U. Siegner: Quantum Metrology, Foundation of Units and Measurement
I.Djodjevic: Quantum Coominication, Quantum Networks and Quantum Sensing

Recent publications and articles

Teaching and learning methods
Lecture, 2 SWS
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<th>Workload</th>
<th>30 h lecture (attendance)</th>
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<tr>
<td></td>
<td>90 h self study</td>
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<td></td>
<td>Total: 120 h</td>
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**Assessment**  
The module examination consists of a graded written or oral examination, depending on the number of participants. If a specified academic work is achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

**Grading procedure**  
The module grade is equal to the examination grade.

**Basis for**  
Quantum Sensing II
## Quantum Sensing II

Modules referring to Electrical Engineering

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<tr>
<td>Cycle</td>
<td>each Summer Semester</td>
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</table>
| Coordinator           | Prof. Dr. Claus Brixmaier  
                       | Lee Kumanchik Ph.D. |
| Instructor(s)         | Lee Kumanchik Ph.D. |

### Allocation of study programmes

- Communications and Computer Engineering M.Sc.
- Electrical Engineering M.Sc.
- Quantum Engineering M.Sc.
- Communication and Information Technology M.Sc.
- Sensorsystemtechnik M.Sc.
- Physics M.Sc.

### Recommended prerequisites

- Contents of basic physics (e.g. Physics for Engineers module) incl. basics of photonics.
- Quantum Sensing I

### Learning objectives

Students who have successfully completed this module,

- have a detailed understanding of the operating principle of quantum sensors,
- know experimental techniques and technologies to realize and control quantum states in quantum sensing instruments,
- know how to apply noise models to calculate sensor performance and make predictions,
- know how to experimentally measure and analyze the intrinsic noise of sensors,
• can learn the basic principles of back-action evading measurements,
• know the techniques for decoupling quantum sensors from the environment, for example, using vacuum systems, thermal shielding, etc.
• know how to implement controllers/servos for environmental stabilization,
• know how to model material behavior with respect to temperature changes,
• know how to model the optical field using various passive and active optical elements commonly found in quantum sensors,
• know how to design optical plug-in boards for quantum sensors,
• can work at the interface between physics and engineering,
• independently deepen their knowledge in the field of quantum sensing and gain strategies for literature review.

Syllabus
In this lecture, the following technical content will be taught:
• Different actual quantum sensors: Atomic/molecular clocks, frequency references, quantum inertial sensors, quantum gravity gradiometers, LIGO,
• Laser servos, temperature controllers, platform stabilizers,
• Noise sources and their origins: electronic noise, optical noise, pressure noise, thermal noise, etc.
• Optical field propagation through linear and nonlinear media,
• Measurement by frequency mixing techniques,
• Optomechanical feedback and optical cavities (cavities),
• Material response to temperature changes and dilatometry,
• Engineering technologies for quantum systems: vacuum technology, detector technology, thermal management, etc.

Literature
F. Schwabl: Quantenmechanik und Quantenmechanik für Fortgeschrittene
T.Fließbach: Quantenmechanik
W.Nawrocki: Introduction to Quantum Metrology
E.Goebel, U.Siegner: Quantum Metrology, Foundation of Units and Measurement
IDjodjevic: Quantum Communication, Quantum Networks and Quantum Sensing

Recent publications and Articles

Lecture notes and slides

Teaching and learning methods
Lecture 2 SWS

Workload
30 h lecture (attendance)
90 h self-study
Total: 120 h

Assessment
The module examination consists of a graded written or oral examination, depending on the number of participants. If a specified academic work is
achieved, a grade bonus is awarded in accordance with §17 (3a) of the General Examination Regulations at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

Grading procedure
The module grade is equal to the examination grade.

Basis for
-
# Technology for Micro- and Nanostructures

Modules referring to Electrical Engineering

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<tr>
<td>Coordinator</td>
<td>Prof. Dr. Peter Unger</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>Prof. Dr. Peter Unger</td>
</tr>
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## Allocation of study programmes

- Electrical Engineering and Information Technology, M.Sc., Elective Module
- Electrical Engineering and Information Technology, M.Sc., Elective Module, Microelectronics
- Electrical Engineering and Information Technology, M.Sc., Optional Module, Automation and Energy Technology
- Communications Technology, M.Sc., Optional technical module, Communications Circuits and Systems

## Recommended prerequisites

- 

## Learning objectives

The students can describe and explain the different lithography methods like optical, e-beam, and x-ray lithography. For a given lithographic problem, they are able to select a suitable exposure process and to choose a proper resist material. The students understand the physics of low-pressure non-equilibrium gas discharges, can give examples of commonly used process techniques using this type of plasma, and are able to sketch the construction of typical plasma-etching and plasma-deposition systems. The students are able to explain the physics of dry-etching and vacuum deposition processes used in semiconductor and thin-film technology.

## Syllabus

At the beginning of the course, the basic technological processes for lithography and pattern transfer techniques are discussed. As applications of these technologies, fabrication processes are presented like CMOS and III-V technology, micromechanics, magnetic thin-film heads, flat-panel displays, micro optics, x-ray optics and quantum-effect electronic devices. The lectures are accompanied by exercises, where important original publications will be discussed and hands-on experiments in the clean room will be performed.
Main Topics:
- Resists
- Optical Lithography
- Electron-Beam Lithography
- X-Ray Lithography
- Wet-Chemical and Dry Etching Techniques
- Film Deposition Processes
- Micromechanics
- Thin-Film Technology
- Nanometer Structures Technology

Literature

Teaching and learning methods
- Lecture “Technology for Micro- and Nanostructures”, 2 SWS
- Exercise “Technology for Micro- and Nanostructures”, 1 SWS

Workload
- Preparation and Evaluation: 45 h
- Active Time: 75 h
- Sum: 120 h

Assessment
- The module examination consists of a graded written or oral examination, depending on the number of participants. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.

Grading procedure
- The module grade is equal to the examination grade.

Basis for
-
### Big Data Analytics - Methods and Applications

**Modules referring to Mobility and Subject-Specific Specialisation**

**Code** 8802874147  
**ECTS credits** 7  
**Attendance time** 4  
**Language of instruction** German  
**Duration** 1  
**Cycle** irregular  
**Coordinator** Mr. Prof. Dr. Klier; Institute of Business Analytics  
**Instructor(s)** Mr. Prof. Dr. Klier; Institute of Business Analytics  

**Allocation of study programmes**  

**Recommended prerequisites** none

**Learning objectives**  
Today, companies have access to very extensive and ever-growing amounts of data - for example, via social media and the Internet (e.g., online social networks, wikis, rating and review communities, discussion forums), but also in traditional databases (e.g., data warehouses, customer databases). The target-oriented and well-founded analysis of these data enables improved decision support and bears great potential in a wide variety of application areas (e.g., innovation management, product development, marketing, customer relationship management, internal knowledge management). The module "Big Data Analytics – Methoden und Anwendungen" teaches and applies the necessary fundamentals and methods. Students who have successfully completed this module know the essential theoretical principles, potential use cases, and risks of Big Data Analytics and are able to explain them. They are familiar with various methods for analyzing large amounts of structured and unstructured data (e.g., collaborative and content-based filtering, (recurrent) neural networks, methods from the field of Explainable Artificial Intelligence) and can assess the possibilities and limitations of these and apply them. On this basis, they can independently acquire new areas of knowledge and new methods of Data Science. Furthermore, they are able to...
apply these methods to solve practical problems (e.g. analysis of real data sets using software tools), interpret the results and derive recommendations.

**Syllabus**

The following contents are addressed in this module:

- **Introduction and foundations** – Big Data Analytics as a highly relevant topic
  - Characteristics, opportunities, and risks of Big Data
  - Use cases and (economic) potential of Big Data Analytics

- **Big Data Analytics** – selected fields of application and methods
  - Recommender systems (e.g., collaborative filtering, content-based filtering)
  - Text Mining (e.g., vector space model, word embeddings and neural networks, Explainable Artificial Intelligence)
  - Smart cities (e.g., recurrent neural networks)

- **Big Data Analytics** – practical applications
  - Analysis of real-world data using software tools
  - Solving practical problems, interpreting the results, and deriving recommendations

**Literature**


**Teaching and learning methods**

Lecture (2 SWS) and exercises (2 SWS)

**Workload**

In-class: 80 h
Self-study: 130 h
**In sum: 210 h**

**Assessment**

The grade of the module will be the grade of the written exam. No prerequisites are necessary for exam registration.

**Grading procedure**

The grade of the module will be the grade of the exam.
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<td>Under the following links you will find the assignment of the <a href="#">module to the respective profile area or specialization</a> and to the <a href="#">core area or AQMT (according to FSPO 2022)</a>.</td>
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</table>
Data Mining
Modules referring to Mobility and Subject-Specific Specialisation

Code 8802871994

ECTS credits 6

Attendance time 4

Language of instruction Englisch

Duration 1

Cycle each Summer Semester

Coordinator PD Dr. Friedhelm Schwenker

Instructor(s) PD Dr. Friedhelm Schwenker

Allocation of study programmes
- Informatik, M.Sc., FSPO 2014 Praktische und Angewandte Informatik,
- Informatik, M.Sc., FSPO 2014 Mustererkennung,
- Informatik, M.Sc., FSPO 2014 Neuroinformatik,
- Medieninformatik, M.Sc., FSPO 2014 Praktische und Angewandte Informatik,
- Medieninformatik, M.Sc., FSPO 2014 Mustererkennung,
- Medieninformatik, M.Sc., FSPO 2014 Neuroinformatik,
- Software Engineering, M.Sc., FSPO 2014 Praktische und Angewandte Informatik,
- Cognitive Systems, M.Sc., FSPO 2014 Learning and Memory,
- Informatik, M.Sc., FSPO 2017 Praktische und Angewandte Informatik,
- Informatik, M.Sc., FSPO 2017 Mustererkennung,
- Informatik, M.Sc., FSPO 2017 Neuroinformatik,
- Mathematics, M.Sc., FSPO 2024, compulsory elective modules in the subsidiary subject Computer Science
- Mathematics, M.Sc., FSPO 2024, compulsory elective modules in the multidisciplinary subsidiary subject
- Mathematics and Management, M.Sc., FSPO 2024, compulsory elective modules in Computer Science
- Medieninformatik, M.Sc., FSPO 2017 Praktische und Angewandte Informatik,
- Medieninformatik, M.Sc., FSPO 2017 Mustererkennung,
- Medieninformatik, M.Sc., FSPO 2017 Neuroinformatik,
- Software Engineering, M.Sc., FSPO 2017 Praktische und Angewandte Informatik,
- Cognitive Systems, M.Sc., FSPO 2017 Learning & Memory
- Electrical Engineering and Information Technology
- Quantum Engineering, M.Sc., FSPO 2023, elective

Recommended prerequisites Basic knowledge in programming, analysis, linear algebra and probability theory.
### Learning objectives
Students acquire knowledge about different methods and algorithms of data mining. In exercises, students are able to implement the basic algorithms, and are able to apply data mining principles to technical applications, in clustering, classification and regression.

### Syllabus
In this course the basic topics on data mining are introduced:

- Uni- and multivariate statistical data analysis
- Clusteranalysis
- Visualization and dimensionality reduction
- Mining of association rules
- Classification and regression
- Statistical evaluation of data mining results

### Literature
- Witten, Ian H. und Frank, Eibe: Data mining, Morgan Kaufmann, 2000
- Marco Gori: Machine Learning, Morgan Kaufman, 2018
- Mohammed Zki and Wagner Meira: Data Mining and Machine Learning, Cambridge University Press, 2020

### Teaching and learning methods
Data Mining (Lecture) (2 SWS),
Data Mining (Exercise) (2 SWS)

### Workload
- attendance: 60h
- self-study: 120h
- total: 180h

### Assessment
The module examination consists of a graded written examination. If a specified academic work is achieved, a grade bonus is awarded at the immediately following examination. The examination grade is improved by one grade level, but not better than 1.0. An improvement from 5.0 to 4.0 is not possible.

### Grading procedure
The module grade is equal to the examination grade.

### Basis for
-
## Founder's Garage I - Businessplan

Modules referring to Mobility and Subject-Specific Specialisation

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<td>Coordinator</td>
<td>Prof. Dr. Steffen Zimmermann</td>
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<tr>
<td>Instructor(s)</td>
<td>Dr. Birgit Stelzer, Lena Schmid</td>
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<tr>
<td>Recommended prerequisites</td>
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<tr>
<td>Learning objectives</td>
<td>- Learning and understanding entrepreneurial thinking and acting</td>
</tr>
<tr>
<td></td>
<td>- Development and evaluation of a business model</td>
</tr>
<tr>
<td></td>
<td>- Customer- or user-specific development and testing of a product or service</td>
</tr>
<tr>
<td></td>
<td>- Application of various design thinking and lean startup methods</td>
</tr>
<tr>
<td></td>
<td>- Collaboration in interdisciplinary teams</td>
</tr>
<tr>
<td></td>
<td>- Creation of a business plan</td>
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<tr>
<td></td>
<td>- Acquaintance with and application of presentation methods</td>
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</tbody>
</table>

### Syllabus

Founder’s Garage gives students the opportunity to work on their own projects by developing specific solution approaches based on a challenge or problem. During the seminar, they are given various methodological approaches from the design thinking and lean startup fields (e.g. personas, value proposition canvas, surveys/interviews, development of prototypes) to develop their own business model. For this purpose, they work in small interdisciplinary student groups and also receive support from a coach. Thus, the students not only receive theoretical
input, but can also express themselves creatively and further develop their project management and team skills.

In addition to the face-to-face events (BootCamp, ThrillCamp and the final pitches), emphasis is also placed on independent learning, so that various teaser mails are sent out during the semester to prepare students for the seminar. There are also Q&A sessions during the seminar, for example on financing models or the business plan, which students can attend independently.

<table>
<thead>
<tr>
<th>Literature</th>
<th>This will be announced during the course.</th>
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<tbody>
<tr>
<td>Teaching and learning methods</td>
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<tr>
<td>Workload</td>
<td>180 hours (Attendance time and self-study)</td>
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<td>Assessment</td>
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# Founder's Garage II - Accelerator

Modules referring to Mobility and Subject-Specific Specialisation

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<td>Coordinator</td>
<td>Prof. Dr. Steffen Zimmermann</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>Dr. Birgit Stelzer, Lena Schmid</td>
</tr>
</tbody>
</table>

**Allocation of study programmes**


**Recommended prerequisites**

None

**Learning objectives**

- Learning and understanding entrepreneurial thinking and acting throughout the entire start-up process
- Development and evaluation of an own business model
- Customer- or user-specific development and testing of a product or service
- Application of various design thinking and lean startup methods
- Acquaintance with and application of presentation methods

**Syllabus**

As part of the follow-up module Founder's Garage II - Accelerator, students have the opportunity to participate in an accelerator program such as Start-up BW ASAP with their own idea and to go through this program independently to further develop their own idea. Afterwards, the students have to present their learning outcomes and the work steps they have gone through in a presentation and a final report including reflection.

**Literature**

This will be announced during the course.
### Teaching and learning methods

<table>
<thead>
<tr>
<th>Description</th>
<th>Details</th>
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<tr>
<td>SWS</td>
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### Workload

- 180 hours (Attendance time and self-study)

### Assessment

The module examination consists of a graded written elaboration. Participation in the examination requires that the following module has been passed according to FSPO: “Founder’s Garage I - Business Plan”.

### Grading procedure

The module grade is equal to the examination grade.

### Basis for

-
# Industrial Internship I

Modules referring to Mobility and Subject-Specific Specialisation

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<tr>
<td>Cycle</td>
<td>each Semester</td>
</tr>
<tr>
<td>Coordinator</td>
<td>Dean of Physics Studies</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>All lecturers from the physics and electrical engineering departments.</td>
</tr>
<tr>
<td>Allocation of study programmes</td>
<td>Quantum Engineering M.Sc., elective, 3rd semester</td>
</tr>
<tr>
<td>Recommended prerequisites</td>
<td>-</td>
</tr>
<tr>
<td>Learning objectives</td>
<td>The internship serves to gain subject-related knowledge and experience from professional practice. In addition, the internship provides insights into everyday professional life and prepares students for their career entry.</td>
</tr>
<tr>
<td>Syllabus</td>
<td>The industrial internship covers the typical professional field of physicists and/or engineering-related activities.</td>
</tr>
<tr>
<td>Literature</td>
<td>tba</td>
</tr>
<tr>
<td>Teaching and learning methods</td>
<td>e.g. full-time internship: 8 weeks</td>
</tr>
<tr>
<td>Workload</td>
<td>300 h</td>
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<tr>
<td>Assessment</td>
<td>The module examination consists of an ungraded participation in all phases of the project. The evaluation scheme will be announced at the beginning of the project.</td>
</tr>
</tbody>
</table>
**Grading procedure**  The module is not graded.

**Basis for**  -
### Industrial Internship II

**Modules referring to Mobility and Subject-Specific Specialisation**

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<td><strong>Cycle</strong></td>
<td>each Semester</td>
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<td><strong>Coordinator</strong></td>
<td>Dean of the Physics Studies</td>
</tr>
<tr>
<td><strong>Instructor(s)</strong></td>
<td>All lecturers from the physics and electrical engineering departments</td>
</tr>
<tr>
<td><strong>Allocation of study programmes</strong></td>
<td>Quantum Engineering M.Sc., elective, 3rd semester</td>
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<tr>
<td><strong>Recommended prerequisites</strong></td>
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</tr>
<tr>
<td><strong>Learning objectives</strong></td>
<td>The internship serves to gain subject-related knowledge and experience from professional practice. In addition, the internship provides insights into everyday professional life and prepares students for their career entry.</td>
</tr>
<tr>
<td><strong>Syllabus</strong></td>
<td>The industrial internship covers the typical professional field of physicists and/or engineering-related activities.</td>
</tr>
<tr>
<td><strong>Literature</strong></td>
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<tr>
<td><strong>Teaching and learning methods</strong></td>
<td>e.g. full-time internship: 11 weeks</td>
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<td><strong>Workload</strong></td>
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<td><strong>Assessment</strong></td>
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</table>
Grading procedure  The module is not graded.

Basis for  -
Research Internship
Modules referring to Mobility and Subject-Specific Specialisation

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<tr>
<td>Cycle</td>
<td>each Semester</td>
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<td>Coordinator</td>
<td>Dean of Physics Studies</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>All lecturers from physics and electrical engineering department.</td>
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<tr>
<td>Allocation of study programmes</td>
<td>Quantum Engineering M.Sc., elective module, 3rd semester</td>
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<tr>
<td>Recommended prerequisites</td>
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<tr>
<td>Learning objectives</td>
<td>Students who successfully passe this module learn to familiarize themselves with the research and methodology in the selected institute.</td>
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<tr>
<td>Syllabus</td>
<td>The research internship serves to deepen and apply theoretical knowledge in a practical context. It is intended both to impart subject-specific knowledge in the technologies and to introduce students to organisational problems.</td>
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<tr>
<td>Literature</td>
<td>tba</td>
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<tr>
<td>Teaching and learning methods</td>
<td>e.g. 8 weeks full-time</td>
</tr>
<tr>
<td>Workload</td>
<td>300 h</td>
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<tr>
<td>Assessment</td>
<td>The module examination consists of an ungraded participation in all phases of the project. The evaluation scheme will be announced at the beginning of the project.</td>
</tr>
<tr>
<td>Grading procedure</td>
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</tr>
<tr>
<td>-------------------</td>
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</tr>
<tr>
<td>Basis for</td>
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Successful Project Management - Fundamentals
Modules referring to Mobility and Subject-Specific Specialisation

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<tr>
<td>Cycle</td>
<td>each Winter Semester</td>
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<tr>
<td>Coordinator</td>
<td>Dean of Physics Studies</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>Dr. Volker Kraus</td>
</tr>
</tbody>
</table>

Allocation of study programmes
- Physics M.Sc., elective module
- Wirtschaftsphysik M.Sc., elective module

Recommended prerequisites
None

Learning objectives
Students who have successfully completed this module
- are familiar with the basics of operational project management.
- can independently plan, realize, monitor and control complex interdisciplinary tasks.
- are familiar with the various organizational forms of project management, the coordination of work in project teams, and the requirements and tasks of a project manager.
- are proficient in the basic planning techniques of project management
- are able to use different methods for planning, controlling and monitoring processes based on network planning technology.
- know the challenges of project management by means of practical examples.

Syllabus
1. Motivation, concept formation and basic elements of project management
2. Project environment within an organization
3. The role of the project manager in the company
4. Stakeholder Management
5. Integration Management
6. Content and scope management
7. Scheduling Management
8. Cost Management
9. Quality Management
|------------|------------------------------------------------------------------------|
| Teaching and learning methods | Lecture (2 hours per week)  
Seminar (1 hour per week) |
| Workload | 30 hours lecture  
15 hours seminar  
75 hours self-study  
total: 120 hours |
| Assessment | The module examination consists of a graded written or oral examination, depending on the number of participants. |
| Grading procedure | The module examination consists of a graded written or oral examination, depending on the number of participants. |
| Basis for | Planning and realization of a project |
### Additive Key Qualifications I

**Modules referring to Complementary Area**

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<td>Language of instruction</td>
<td>English or German</td>
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<td>Duration</td>
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<tr>
<td>Cycle</td>
<td>each Semester</td>
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<tr>
<td>Coordinator</td>
<td>Dean of the Physics Studies</td>
</tr>
<tr>
<td>Instructor(s)</td>
<td>Lecturers at the Humboldt and Language Center of Ulm University</td>
</tr>
<tr>
<td>Allocation of study programmes</td>
<td>Quantum Engineering M.Sc., elective module</td>
</tr>
<tr>
<td>Recommended prerequisites</td>
<td>-</td>
</tr>
</tbody>
</table>
| Learning objectives | students who have successfully completed this module  
  - can apply intercultural and foreign language skills as well as/or knowledge and skills in the areas of teamwork, communication and presentation.  
  - are able to reflect, test and evaluate the acquired key competencies as well as transfer and implement them in an argumentative way. |
| Syllabus         | Depending on the course |
| Literature       | Depending on the course |
| Teaching and learning methods | e.g. 2 classroom hours |
| Workload         |  
  - attendance: 30 h  
  - self-study: 60 h  
  - total: 90 h |
<table>
<thead>
<tr>
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<tr>
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<td><strong>Basis for</strong></td>
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Additive Key Qualifications II
Modules referring to Complementary Area

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<td>Language of instruction</td>
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<td>2</td>
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<tr>
<td>Cycle</td>
<td>each Winter Semester</td>
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<tr>
<td>Coordinator</td>
<td>Dean of Physics Studies</td>
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<tr>
<td>Instructor(s)</td>
<td>Lecturers at the Humboldt and Language Center of Ulm University</td>
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<tr>
<td>Allocation of study programmes</td>
<td>Quantum Engineering M.Sc., elective module</td>
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<tr>
<td>Recommended prerequisites</td>
<td>-</td>
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</tbody>
</table>
| Learning objectives     | students who have successfully completed this module
|                         | • can apply intercultural and foreign language skills as well as/or knowledge and skills in the areas of teamwork, communication and presentation.
|                         | • are able to reflect, test and evaluate the acquired key competencies as well as transfer and implement them in an argumentative way. |
| Syllabus                | Depending on the course |
| Literature              | Depending on the course |
| Teaching and learning methods | e.g. two classroom hours |
| Workload                | attendance: 30 h
|                         | self-study: 60 h
<p>|                         | total: 90 h |</p>
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Additive Key Qualifications III
Modules referring to Complementary Area

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<td>Language of instruction</td>
<td>English and German</td>
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<td>Duration</td>
<td>2</td>
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<tr>
<td>Cycle</td>
<td>each Winter Semester</td>
</tr>
<tr>
<td>Coordinator</td>
<td>Dean of Physics Studies</td>
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<tr>
<td>Instructor(s)</td>
<td>Lecturers at the Humboldt and Language Center of Ulm University</td>
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<tr>
<td>Allocation of study programmes</td>
<td>Quantum Engineering M.Sc., elective module</td>
</tr>
<tr>
<td>Recommended prerequisites</td>
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</tr>
<tr>
<td>Learning objectives</td>
<td>students who have successfully completed this module</td>
</tr>
<tr>
<td></td>
<td>• can apply intercultural and foreign language skills as well as/or knowledge and skills in the areas of teamwork, communication and presentation.</td>
</tr>
<tr>
<td></td>
<td>• are able to reflect, test and evaluate the acquired key competencies as well as transfer and implement them in an argumentative way</td>
</tr>
<tr>
<td>Syllabus</td>
<td>Depending on the course</td>
</tr>
<tr>
<td>Literature</td>
<td>Depending on the course</td>
</tr>
<tr>
<td>Teaching and learning methods</td>
<td>e.g. 2 classroom hours</td>
</tr>
<tr>
<td>Workload</td>
<td>attendance: 30 h</td>
</tr>
<tr>
<td></td>
<td>self-study: 60 h</td>
</tr>
<tr>
<td></td>
<td>total: 90 h</td>
</tr>
<tr>
<td><strong>Assessment</strong></td>
<td>The module examination consists of a graded written or oral examination, depending on the number of participants. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.</td>
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<tr>
<td>---------------</td>
<td>--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
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<tr>
<td><strong>Grading procedure</strong></td>
<td>The module grade is equal to the examination grade.</td>
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<td><strong>Basis for</strong></td>
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## Additive Key Qualifications IV

*Modules referring to Complementary Area*

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<td>Cycle</td>
<td>each Semester</td>
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<td>Dean of Physics Studies</td>
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<td>Instructor(s)</td>
<td>Lecturers at the Humboldt and Language Center of Ulm University</td>
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<td>Allocation of study programmes</td>
<td>Quantum Engineering M.Sc., elective module</td>
</tr>
<tr>
<td>Recommended prerequisites</td>
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</tbody>
</table>

### Learning objectives

- students who have successfully completed this module
  - can apply intercultural and foreign language skills as well as/or knowledge and skills in the areas of teamwork, communication and presentation.
  - are able to reflect, test and evaluate the acquired key competencies as well as transfer and implement them in an argumentative way.

### Syllabus

Depending on the course

### Literature

Depending on the course

### Teaching and learning methods

e.g. 2 classroom hours

### Workload

- attendance: 30 h
- self-study: 60 h
- total: 90 h
<table>
<thead>
<tr>
<th><strong>Assessment</strong></th>
<th>The module examination consists of a graded written or oral examination, depending on the number of participants. The examination form will be announced in good time before the examination is held - at least 4 weeks before the examination date.</th>
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<tr>
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<td>The module grade is equal to the examination grade.</td>
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<tr>
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