Module Descriptions

Master of Science Quantum Engineering

Examination Regulations in the Version of: 2023

Index

Compulsory Area

Compulsory Elective Area

Adaptation

Quantum Physics

Electrical Engineering

Advanced Seminar Quantum Engineering

Modules referring to Compulsory Area

Code	8802875525
ECTS credits	3
Attendance time	2
Language of instruction	English
Duration	1
Cycle	each Summer Semester
Coordinator	Dean of Physics Studies
Instructor(s)	All physics lecturers
Allocation of study programmes	Quantum Engineering M.Sc., 1st or 2nd Semester
Recommended prerequisites	B.Sc. degree in Physics or Electrical Engineering
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

Assessment	The module examination consists of completing an assignement on a given topic and a graded and the graded oral presentation of the results and participation in the discussion.
Grading procedure	The module grade is equal to the examination grade.
Basis for	Preparation of scientific lectures and presentation of own results.

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

Literature	tba
Teaching and learning methods	2 SWS, Lecture
Workload	30 h lecture (attandance) 60 h self-study Total: 90 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	-

Master's Thesis

Modules referring to Compulsory Area

Code	8802880000
ECTS credits	30
Attendance time	*keine Angaben*
Language of instruction	English
Duration	1
Cycle	each Semester
Coordinator	Dean of Physics Studies
Instructor(s)	All physics and electrical engineering lecturers
Allocation of study programmes	Quantum Engineering M.Sc., Final projects, 4th semester.
Recommended prerequisites	Formal requirements: Passing the module "Research Project - QE" and the acquisition of at least 75 ECTS. Approval of the Examination Board that the topic meets the scientific requirements of the degree program (FSPO §8). Recommended prior knowledge: Lectures from the subject area of the Master's thesis.
Learning objectives	The students • have acquired the competence to work independently on a topic from current research in quantum engineering and to develop their own solutions. • are able to write a scientific written elaboration on the results obtained. • are able to justify their solutions in a scientific discussion and present their own point of view convincingly. • have learned to integrate themselves into a research team.
Syllabus	• Carrying out an experimental or theoretical research project • Evaluation of the results obtained • Discussion of the results in connection with the specialist literature

- Documentation of the research project

Literature	tba
Teaching and learning methods	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.
Workload	900 h
Assessment	The module examination consists of completing an assignement on a given scientific topic and a graded written thesis.
Grading procedure	The module grade is equal to the examination grade.
Basis for	-

Research Project - QE

Modules referring to Compulsory Area

Code	8802875527
ECTS credits	15
Attendance time	*keine Angaben*
Language of instruction	English
Duration	1
Cycle	each Semester
Coordinator	No English version available yet.
Instructor(s)	All professors in the selected institute.
Allocation of study programmes	Quantum Engineering M. Sc., compulsory area, 3rd semester
Recommended prerequisites	Skills in Quantum Physics and Electrical Engineering.
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.

Workload	450 hours
Assessment	The module examination consists of a graded written elaboration.
Grading procedure	The module grade is equal to the examination grade.
Basis for	Master's thesis

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 Engineerung 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	• K. Jänich. Mathematik 1,2. Mathematik: geschrieben für Physiker. Springer, 2002. • H. Kerner and W. von Wahl. Mathematik für Physiker. Springer-Lehrbuch. Springer Berlin Heidelberg, 2007. • K. Meyberg and P. Vachenauer. Höhere Mathematik 1,2. Höhere Mathematik. Springer Berlin Heidelberg, 2003. • H. von Mangoldt and K. Knopp. Höhere Mathematik: eine Einführung für Studierende und zum Selbststudium. Höhere Mathematik / v. Mangoldt, Knopp. Hirzel, 1990. • W. Walter. Gewöhnliche Differentialgleichungen: Eine Einführung. Springer-Lehrbuch. Springer Berlin Heidelberg, 2000. • D. Werner. Einführung in die höhere Analysis: topologische Räume, Funktionentheorie, gewöhnliche Differentialgleichungen, Mass- und Integrationstheorie, Funktionalanalysis. Springer, 2006.
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

Code	8802872269
ECTS credits	6
Attendance time	4
Language of instruction	English (Summer Term) / German (Winter Term)
Duration	1
Cycle	each Semester
Coordinator	Prof. Dr.-Ing. Maurits Ortmanns
Instructor(s)	Prof. Dr.-Ing. Maurits Ortmanns
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
- Razavi, B. “Design of Analog CMOS Integrated Circuits”, McGraw-Hill
- Johns, D. “Analog Integrated Circuit Design”, 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

Code	8802872473
ECTS credits	5
Attendance time	4
Language of instruction	english
Duration	1
Cycle	each Summer Semester
Coordinator	Prof. Dr.-Ing. Christian Waldschmidt
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

Code	8802875276
ECTS credits	4
Attendance time	2
Language of instruction	English
Duration	1
Cycle	each Winter Semester
Coordinator	Prof. Claus Braxmaier
Instructor(s)	Dr. Lisa Wörner
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
	• Prerequisits 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 R. Haberfellner, et al.: Systems Engineering: Grundlagen und Anwendungen 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.

Grading procedure	The module grade is equal to the examination grade.
Basis for	Advanced Quantum Engineering

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 hours 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

Literature	• Cohen- Tannoudji, Quantenmechanik. Bd. 1, Bd. 2 (teilweise) • Schwabl, Quantenmechanik • Messiah, Quantenmechanik, Bd. 1 • Fick, Einführung in die Grundlagen der Quantentheorie
Teaching and learning methods	Lecture (4 hours per week) Exercise (2 hours per week)
Workload	60 hours lecture (attendance) 30 hours exercise (attendance) 150 hours self-study and exam preparation Total: 240 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	Modules Solid state physics, nuclear, particle and astrophysics, thermodynamics and statistics, advanced methods of quantum mechanics

Signals and Systems

Modules referring to Adaptation

Code	8802870381
ECTS credits	8
Attendance time	8
Language of instruction	No english version available yet.
Duration	1
Cycle	each Winter Semester
Coordinator	Prof. Dr.-Ing.Robert Fischer
Instructor(s)	No english version available yet.
Allocation of study programmes	Electrical Engineering and Information Technology Computational Sciene and Computer Engineering B.Sc.
Recommended prerequisites	No english version available yet.
Learning objectives	No english version available yet.
Syllabus	No english version available yet.
Literature	No english version available yet.
Teaching and learning methods	No english version available yet.
Workload	No english version available yet.
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	No english version available yet.

Condensed Matter Theory A: Quantum Mechanics on Macroscopic Scales

Modules referring to Quantum Physics

Code	8802876067
ECTS credits	6
Attendance time	5
Language of instruction	English
Duration	1
Cycle	each Winter Semester
Coordinator	Dean of Physics Studies
Instructor(s)	Prof. Dr. Joachim Ankerhold, Dr. Björn Kubala, Dr. Ciprian Padurariu
Allocation of study programmes	Physics M.Sc., elective
Recommended prerequisites	Quantum mechanics, solid state physics, thermodynamics/statistics
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 completelynew 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 HouchesLectures, with Uri Vool, arXiv:1610.03438 • Tero T. Heikkilä,The Physics of Nanoelectronics: Transport and FluctuationPhenomena at Low Temperatures • P. Breuer and F. Petruccione, The Theory of Open Quantum Systems, OxfordUniversity Press
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 • Topology: web course on Topology in CM (Anton Akhmerov et al., TU Delft) 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:

- C. C. Gerry and P. L. Knight, Introductory Quantum Optics (Cambridge University Press, Cambridge, 2005)
- G. Grynberg, A. Aspect and C. Fabre, Introduction to Quantum Optics
- R. Loudon, The Quantum Theory of Light (Oxford university Press)
- M. O. Scully and M. S. Zubairy, Quantum Optics (Cambridge University Press, Cambridge, 1997)

More specialized books:

- C. Cohen-Tannoudji, J. Dupont-Roc, and G. Grynberg, Atom-Photon Interactions (Wiley-Interscience); comment: specialized on Light Atom Interaction
- S. Haroche, J. M. Raimond, Exploring hte Quantum, (Oxford University Press 2006); comment: specialized on cavity QED

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

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Introduction to Nuclear Magnetic Resonance

Modules referring to Quantum Physics

Code	8802877108
ECTS credits	6
Attendance time	5
Language of instruction	English
Duration	1
Cycle	each Winter Semester
Coordinator	Dean of Physics Studies
Instructor(s)	Dr. Raiker Witter
Allocation of study programmes	Physics M.Sc., D - Examination Field Master Programmes, E - Examination Field General Range of Studies, 1st or 2nd 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 bio-medicine); • 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
- Electron Paramagnetic Resonance Spectroscopy: Fundamentals, Patrick Bertrand, Springer, 2020
- Handbook of High Field Dynamic Nuclear Polarization, Vladimir K. Michaelis et at., 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

Code	8802874198
ECTS credits	3
Attendance time	2
Language of instruction	English
Duration	1
Cycle	each Summer Semester
Coordinator	Dean of Physics Studies
Instructor(s)	Dr. Siyushev
Allocation of study programmes	M. Sc. Physics, elective module, 1st or 2nd semester
Recommended prerequisites	Classical electrodynamics
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	Reaserch 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

Teaching and learning methods	Lecture (3 hours per week) Exercise (1 hours per week)
Workload	45 hours lecture (attendance time) 30 hours exercise (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. 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.
Grading procedure	The module grade is equal to the examination grade.
Basis for	-

Open Quantum Systems

Modules referring to Quantum Physics

Code	8802871766
ECTS credits	6
Attendance time	5
Language of instruction	English
Duration	1
Cycle	each Winter Semester
Coordinator	Dean of Physics Studies
Instructor(s)	Prof. Susana Huelga
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	• M.A. Nielsen and I. Chuang, ”Quantum Computing and Quantum Information”, Cambridge University Press • 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); • Dunjko and Briegel, ”Machine learning & artificial intelligence in the quantum domain, Rep. Prog. Phys. **81**, 074001 (2018).

Teaching and learning methods	Lecture (2 hours per week) Exercise (1 hours per week)
Workload	30 hours lecture (attendance time) 15 hours exercise (attendance time) 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 grade is equal to the examination grade.
Basis for	Research in the field of Quantum Technologies.

Quantum Computing
Modules referring to Quantum Physics

Code	8802871820
ECTS credits	6
Attendance time	4
Language of instruction	Deutsch oder Englisch
Duration	1
Cycle	irregular
Coordinator	Dean of Physics Studies
Instructor(s)	Prof. Dr. Jacobo Torán
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	• Michael A. Nielsen and Isaac L. Chuang. Quantum Computation and Quantum Information. Cambridge University Press 2000. • Mika Hirvensalo. Quantum Computing. Springer 2001. • lecture notes
Teaching and learning methods	Lecture Quantum Computing, 2 classroom hours Exercise Quantum Computing, 1 classroom hour
Workload	Attendence: 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

Code	8802877081
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. Birger-Horstmann
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	• Nielsen, M. and Chuang, I., Quantum Computation and Quantum Information. Cambridge University Press, 2000. • John Preskill, Lecture notes on quantum information theory, available at http://theory.calytech.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 Coominication, 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

Code	8802875482
ECTS credits	4
Attendance time	2
Language of instruction	english
Duration	1
Cycle	each Summer Semester
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	-

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	Ouantum 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

Literature	tba
Teaching and learning methods	Lecture 3 classroom hours Exercise 2 classroom hours
Workload	45 hours lecture (attendance time) 30 hours exercise (attendance time) 105 hours private 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 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	-

Seminar Quantum Sensing and Metrology

Modules referring to Quantum Physics

Code	8802875068
ECTS credits	3
Attendance time	2
Language of instruction	English
Duration	1 Semester
Cycle	each Winter Semester
Coordinator	Dean of Physics Studies
Instructor(s)	Prof. Dr. Fedor Jelezko, Prof. Dr. Peter Reineker
Allocation of study programmes	Physics M.Sc., elective module, 1^{st} or 2^{nd} semester Wirtschaftsphysik M.Sc., elective module, 1^{st} - 3^{nd} 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	PPhysics 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	**Topics** 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	-

Teaching and learning methods	Seminar (2 hours per week)
Workload	30 hours Seminar 60 hours talk preparation Total: 90 hours
Assessment	The module examination consists of completing an assignement on a given topic and a graded oral presentation of the results as well as participating in the discussion.
Grading procedure	The module grade is equal to the examination grade.
Basis for	Research in quantum technology

Theoretical Quantum Optics

Modules referring to Quantum Physics

Code	8802871420
ECTS credits	6
Attendance time	5
Language of instruction	English
Duration	1
Cycle	each Summer Semester
Coordinator	Dean of Physics Studies
Instructor(s)	Prof. Martin B. Plenio, Dr. Jaemin Lim
Allocation of study programmes	Physics M.Sc., elective module, 1^{st} or 2^{nd} 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) • R. J. Glauber, Quantum Theory of Optical Coherence (Wiley-VCH, Weinheim, 2007) • C.C. Gerry and P.L. Knight, Introductory Quantum Optics (Cambridge University Press, Cambridge, 2005)

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	• M.A. Nielsen and I. Chuang, ”Quantum Computing and Quantum Information”, Cambridge University Press • 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

Code	8802871504
ECTS credits	6
Attendance time	6
Language of instruction	English
Duration	1
Cycle	each Summer Semester
Coordinator	Dean of Physics Studies
Instructor(s)	Prof. Johannes Hecker Denschlag
Allocation of study programmes	Physics M.Sc., elective module, 1^{st} or 2^{nd} semester
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

Code	8802875278
ECTS credits	4
Attendance time	2
Language of instruction	No English version available yet.
Duration	1
Cycle	each Winter Semester
Coordinator	Prof. Claus Braxmaier
Instructor(s)	Dr. Lisa Wörner
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 R. Haberfellner, et al.: Systems Engineering: Grundlagen und Anwendungen 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

Code	8802870422
ECTS credits	8
Attendance time	6
Language of instruction	English
Duration	1
Cycle	each Summer Semester
Coordinator	Prof. Dr. Robert Fischer
Instructor(s)	Prof. Dr. Robert Fischer
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, muti-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 muti-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 sudents 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 Shannons 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-Willems 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

Code	8802870446
ECTS credits	5
Attendance time	4
Language of instruction	english and german
Duration	1
Cycle	each Summer Semester
Coordinator	Prof. Dr.-Ing. Peter Unger
Instructor(s)	Prof. Dr.-Ing. Peter Unger
Allocation of study programmes	Electrical Engineering and Information Technology, M.Sc., Elective Module Communications Technology, M.Sc., Optional Lab Course, Communications Circuits and Systems
Recommended prerequisites	Lecture "Semiconductor Technology" or "Modern Semiconductor Devices"
Learning objectives	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-technologyequipment. 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 capacitancevoltage measurements. The students evaluate the influence of scaling parameters (geometry, size) on the electrical behaviour of the devices (output- and transfer-characteristics).
Syllabus	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

- 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	- Jackson, K. A. / Schröter, W. (Hrsg.) Handbook of Semiconductor Technology, 2000 ISBN-13: 978-3-527-29970-6 - Wiley-VCH, Weinheim - Pierret, R.F.: Field Effect Devices, (Modular Series on Solid State Devices, Vol. 4), Addison- Wesley Reading, 1983 - Zambuto, M.: Semiconductor Devices, McGraw Hill New York, 1989 - C. Y. Chang, F. Kai: GaAs High-Speed Devices: Physics, Technology, and Circuit Applications Wiley, 1994
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
Literature	• B. Razavi, Design of Integrated Circuits for Optical Communications, McGraw-Hill, 2003 • E. Säckinger, Broadband Circuits for Optical Fiber Communication, Wiley,2005
Teaching and learning methods	Classroom hours (3 SWS) Exercise courses (1 SWS)
Workload	Lecture: 42h Exercise: 14h Exercise Preparation: 28h Self-Study: 60h Exam Preparation: 36h Total: 180h
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

Teaching and learning methods	Classroom Lectures (3 SWS) Exercise Courses (1 SWS)
Workload	Lecture: 42h Exercise: 14h Exercise Preparation: 28h Self-Study: 60h Exam Preparation: 36h Total: 180h
Assessment	The module examination consists of a graded oral examination.
Grading procedure	The module grade is equal to the examination grade.
Basis for	Project High-Frequency Amplifier Design Master thesis at the Institute of Electronic Devices and Circuits.

Integrated Interface Circuits

Modules referring to Electrical Engineering

Code	8802872274
ECTS credits	6
Attendance time	4
Language of instruction	English (Deutsch nur nach vorheriger Abstimmung mit den Studierenden)
Duration	1
Cycle	each Summer Semester
Coordinator	Prof. Dr.-Ing Maurits Ortmanns
Instructor(s)	Prof. Dr.-Ing Maurits Ortmanns
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 on 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 cicuits and systems
   e. Charge Balancing Strategies
   f. Applications: Cardiac devices, Neuromuscular simulators, Gastrointestinal devices and obesitytreatment, Drug delivery devices and infusion pumps, Diabetes treatment, Rehabilitation Engineering
   g. Examples for implantable biosensors

Literature

- Gerard Meijer, Michiel Pertijs, Kofi Makinwa, Smart Sensor Systems: Emerging Technologies and Applications, 2014, John Wiley & Sons, Ltd, Print ISBN: 9780470686003
- Marcel Pelgrom, Analog-to-Digital Conversion (Englisch), 2016, Springer, ISBN**:** 3319449702
- Rahul Sarpeshkar, Ultra Low Power Bioelectronics: Fundamentals, Biomedical Applications, and Bio-Inspired Systems, 2010, Cambridge University Press
- M. Ortmanns, F. Gerfers, Continuous-Time Sigma-Delta A/D Conversion: Fundamentals, Performance Limits and Robust Implementations, Springer, 2006, ISBN 364206664X
- S. Pavan, R. Schreier, G.C. Temes, Understanding Delta-Sigma Data Converters, IEEE Press, 2017, ISBN 1119258278

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: 44h 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 successfull 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 di_erent 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,
- amplifers (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

Code	8802871723
ECTS credits	6
Attendance time	4
Language of instruction	English
Duration	1
Cycle	each Summer Semester
Coordinator	apl. Prof. Dr.-Ing. habil. Rainer Michalzik
Instructor(s)	apl. Prof. Dr.-Ing. habil. Rainer Michalzik
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

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	Advanced Optoelectronic Communication Systems, Active Optoelectronic Devices

Quantum Sensing I

Modules referring to Electrical Engineering

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 Coominication, 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 Electrical Engineering

Code	8802875482
ECTS credits	4
Attendance time	2
Language of instruction	english
Duration	1
Cycle	each Summer Semester
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

Code	8802870458
ECTS credits	4
Attendance time	3
Language of instruction	English
Duration	1
Cycle	each Winter Semester
Coordinator	Prof. Dr. Peter Unger
Instructor(s)	Prof. Dr. Peter Unger
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 EnergyTechnology 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	- Marc J. Madou, Fundamentals of Microfabrication, 2nd edition, CRC Press, Bota Raton, 2002 - Henry I. Smith, Submicron- and nanometer-structures technology, 2nd edition, NanoStructures Press, 437 Peakham Road, Sudbury, MA 01776, USA, 1994 - L.F. Thompson, C.G. Willson, and M.J. Bowden, Introduction to Microlithography, 2nd edition, ACS Professional Reference Book, American Chemical Society, 1994 - Brian Chapman, Glow Discharge Processes – Sputtering and Plasma Etching, John Wiley and Sons, New York, 1980 - R.J. Shul, S.J. Pearton (Editors), Handbook of Advanced Plasma Processing Techniques, Springer-Verlag, Heidelberg, 2000
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	M.Sc. Wirtschaftswissenschaften, M.Sc. Mathematical Data Science, M.Sc. Wirtschaftschemie, M.Sc. Wirtschaftsphysik und Studiengänge mit Nebenfach Wirtschaftswissenschaften Mathematics, M. Sc., FSPO 2024, compulsory elective modules in the multidisciplinary subsidiary subject Mathematics and Management, M. Sc., FSPO 2024, compulsory elective modules in Management and Economics
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

- Arrieta et al. (2020) Explainable Artificial Intelligence (XAI): Concepts, taxonomies, opportunities and challenges toward responsible AI. Information Fusion.
- Devlin, J., et al. (2018) Bert: Pre-training of deep bidirectional transformers for language understanding. arXiv:1810.04805
- Leskovec, J., Rajaraman, A., Ullman, J.-D. (2014) Mining of Massive Datasets. Cambridge University Press, Cambridge.
- Loshin, D. (2013) Big Data Analytics: from Strategic Planning to Enterprise Integration with Tools, Techniques, NoSQL, and Graph. Elsevier, Waltham.
- Mikolov, T., et al. (2013) Efficient estimation of word representations in vector space. arXiv:1301.3781

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.

Basis for	Mandatory elective business economics Under the following links you will find the assignment of the module to the respective profile area or specialization and to the core area or AQMT (according to FSPO 2022).

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	• Mitchell, Tom: Machine Learning, Mc Graw Hill, 1997 • Bishop, Chris: Pattern Recognition and Machine Learning, Springer, 2007 • Hand, David und Mannila, Heikki und Smyth, Padhraic: Principles of Data Mining, MIT Press, 2001 • 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, Ca,bridge 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

Code	8802875467
ECTS credits	6
Attendance time	4
Language of instruction	german
Duration	1
Cycle	each Summer Semester
Coordinator	Prof. Dr. Steffen Zimmermann
Instructor(s)	Dr. Birgit Stelzer, Lena Schmid
Allocation of study programmes	M.Sc. Chemie, M.Sc. Wirtschaftswissenschaften, M.Sc. Biochemie, M.Sc. Informatik, M.Sc. Informationssystemtechnik, M.Sc. Elektrotechnik, M.Sc. Physik, M.Sc. Biophysik, M.Sc. Nachhaltige Unternehmensführung, M.Sc. Psychologie, M.Sc. Biologie, M.Sc. Elektrotechnik und Informationstechnologie
Recommended prerequisites	None
Learning objectives	- Learning and understanding entrepreneurial thinking and acting - Development and evaluation of a business model - Customer- or user-specific development and testing of a product or service - Application of various design thinking and lean startup methods - Collaboration in interdisciplinary teams - Creation of a business plan - Acquaintance with and application of presentation methods
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.
Literature	This will be announced during the course.
Teaching and learning methods	4 SWS
Workload	180 hours (Attendance time and self-study)
Assessment	The module examination consists of a graded written elaboration.
Grading procedure	The module grade is equal to the examination grade.
Basis for	Wahlpflicht BWL, With the following links you will find the assignment of the module to the respective profile area or focus and to the core area or AQMT (according to FSPO 2022).

Founder's Garage II - Accelerator

Modules referring to Mobility and Subject-Specific Specialisation

Code	8802875468
ECTS credits	6
Attendance time	4
Language of instruction	german
Duration	1
Cycle	each Semester
Coordinator	Prof. Dr. Steffen Zimmermann
Instructor(s)	Dr. Birgit Stelzer, Lena Schmid
Allocation of study programmes	M.Sc. Biology, M.Sc. Computer Science, M.Sc. Physics, M.Sc. Physics and Management
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	4 SWS
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

Code	8802875540
ECTS credits	10
Attendance time	*keine Angaben*
Language of instruction	English
Duration	1
Cycle	each Semester
Coordinator	Dean of Physics Studies
Instructor(s)	All lecturers from the physics and electrical engineering departments.
Allocation of study programmes	Quantum Engineering M.Sc., elective, 3rd semester
Recommended prerequisites	-
Learning objectives	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.
Syllabus	The industrial internship covers the typical professional field of physicists and/or engineering-related activities.
Literature	tba
Teaching and learning methods	e.g. full-time internship: 8 weeks
Workload	300 h
Assessment	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.

Grading procedure	The module is not graded.
Basis for	-

Industrial Internship II

Modules referring to Mobility and Subject-Specific Specialisation

Code	8802875541
ECTS credits	15
Attendance time	*keine Angaben*
Language of instruction	English
Duration	1
Cycle	each Semester
Coordinator	Dean of the Physics Studies
Instructor(s)	All lecturers from the physics and electrical engineering departments
Allocation of study programmes	Quantum Engineering M.Sc., elective, 3rd semester
Recommended prerequisites	-
Learning objectives	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.
Syllabus	The industrial internship covers the typical professional field of physicists and/or engineering-related activities.
Literature	tba
Teaching and learning methods	e.g. full-time internship: 11 weeks
Workload	450 h
Assessment	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.

Grading procedure	The module is not graded.
Basis for	-

Research Internship

Modules referring to Mobility and Subject-Specific Specialisation

Code	8802875542
ECTS credits	10
Attendance time	*keine Angaben*
Language of instruction	English
Duration	1
Cycle	each Semester
Coordinator	Dean of Physics Studies
Instructor(s)	All lecturers from physics and electrical engineering department.
Allocation of study programmes	Quantum Engineering M.Sc., elective module, 3rd semester
Recommended prerequisites	-
Learning objectives	Students who successfully passe this module learn to familiarize themselves with the research and methodology in the selected institute.
Syllabus	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.
Literature	tba
Teaching and learning methods	e.g. 8 weeks full-time
Workload	300 h
Assessment	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.

Grading procedure	The module is not graded.
Basis for	-

Successful Project Management - Fundamentals

Modules referring to Mobility and Subject-Specific Specialisation

Code	8802875234
ECTS credits	4
Attendance time	3
Language of instruction	English
Duration	1
Cycle	each Winter Semester
Coordinator	Dean of Physics Studies
Instructor(s)	Dr. Volker Kraus
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

10. Personnel or resource management
11. Communication Management
12. Risk Management
13. Procurement Management

Literature	A Guide to the Project Management Body of Knowledge, sixth Edition, 2017.
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

Code	8802886100
ECTS credits	*keine Angaben*
Attendance time	*keine Angaben*
Language of instruction	English or German
Duration	1
Cycle	each Semester
Coordinator	Dean of the Physics Studies
Instructor(s)	Lecturers at the Humboldt and Language Center of Ulm University
Allocation of study programmes	Quantum Engineering M.Sc., elective module
Recommended prerequisites	-
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

Assessment	*not specified*
Grading procedure	*not specified*
Basis for	-

Additive Key Qualifications II

Modules referring to Complementary Area

Code	8802886200
ECTS credits	*keine Angaben*
Attendance time	*keine Angaben*
Language of instruction	English and German
Duration	2
Cycle	each Winter Semester
Coordinator	Dean of Physics Studies
Instructor(s)	Lecturers at the Humboldt and Language Center of Ulm University
Allocation of study programmes	Quantum Engineering M.Sc., elective module
Recommended prerequisites	-
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 total: 90 h

Assessment	*not specified*
Grading procedure	*not specified*
Basis for	**-**

Additive Key Qualifications III

Modules referring to Complementary Area

Code	8802886300
ECTS credits	*keine Angaben*
Attendance time	*keine Angaben*
Language of instruction	English and German
Duration	2
Cycle	each Winter Semester
Coordinator	Dean of Physics Studies
Instructor(s)	Lecturers at the Humboldt and Language Center of Ulm University
Allocation of study programmes	Quantum Engineering M.Sc., elective module
Recommended prerequisites	-
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

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	-

Additive Key Qualifications IV

Modules referring to Complementary Area

Code	8802886400
ECTS credits	*keine Angaben*
Attendance time	*keine Angaben*
Language of instruction	English or German
Duration	2
Cycle	each Semester
Coordinator	Dean of Physics Studies
Instructor(s)	Lecturers at the Humboldt and Language Center of Ulm University
Allocation of study programmes	Quantum Engineering M.Sc., elective module
Recommended prerequisites	-
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

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	-