Attention:

This English version of the module catalogue MA Quantum Engineering is not legally binding. Only the original German text has some legally binding,which you can find under the following link:

https://www.maphy.uni-hannover.de/de/studium/im-studium/modulkatalog

This version has been automatically translated with DeepL and hasonly been checked superficially for errors, so please note the following limitations:

- technical and legal terms may be incorrect
- the names of modules and courses have been translated

With these limitations, we hope that this version is helpful for you.

Master's programme Quantum Engineering

Module catalogue

(shortened)

Status 15.03.2023

Faculty of Mathematics and Physics
of Leibniz Universität Hannover

in conjunction with
of the QUEST Leibniz Research School

in cooperation with
of the Technical University of Braunschweig

ContactDean of Studies of
the Faculty of Mathematics and Physics
Appelstr. 11 A
30167 Hanover
Tel.: 0511/ 762-4466
studiensekretariat@maphy.uni-hannover.de

Dean of StudiesProf. Dr Detlev Ristau
Appelstr. 11 A
30167 Hanover
studiendekan@maphy.uni-hannover.de

Programme CoordinationDipl .
Ing. Axel Köhler
Dr. Katrin Radatz
Dipl.-Soz.Wiss. Miriam Redlich
Appelstr. 11 A
30167 Hanover
Tel.: 0511/ 762-5450
sgk@maphy.uni-hannover.de

Preliminary remark

This document consists of the module catalogue, it presents the modules and their courses.

The module catalogue should also be understood as a supplement to the examination regulations. The current version of the examination regulations can be found at:

https:// www.uni-hannover.de/de/studium/im-studium/pruefungsinfos-fachberatung/studiengang/ordnungen-2

Table of contents

Please note that the legally binding wording of all examination regulations is exclusively that published in the university's announcements.

Access requirement:

The **Master's degree programmes** are subject to admission restrictions. The exact rules (including exceptions) can be found in the respective admission regulations:

www.uni-hannover.de/bewerbung-und-zulassung/voraussetzungen-zum-studium

The application deadline for admission to a Master's degree programme is 15 July for the winter semester (31 May for non-EU citizens) and 15 January for the summer semester (30 November of the previous year for non-EU citizens).

The study:

The study contents are divided into so-called **modules.** A module is a thematic summary of courses. Therefore, more than one course can belong to a module. In addition to lectures, which are usually accompanied by exercises, laboratories and seminars also contribute to the education. To successfully complete a degree programme, students must complete **coursework** and **examinations in the** individual modules.

As a rule, a minimum number of points from exercises is required for coursework. Assessments of coursework do not count towards the final grade. Course achievements can be repeated as often as desired.

The contents of a module are examined as an examination during the course of study, usually by means of an oral examination or a written examination.

So-called **credit points** are assigned to each module according to the expected workload. After completing the required coursework **and** examinations, students are credited with the credit points assigned to the module.

Credit points according to the *European Credit Transfer and Accumulation System* (ECTS) describe the effort required to acquire the competence imparted by a module. One credit point (LP) corresponds to an estimated workload of 30 hours. Approximately 30 credit points are to be acquired per semester.

At least **120 credit points must be** earned in the **Master**'s degree programmes. The modules extend over one to two semesters. As a rule, they each require a workload of between 150 and 300 hours, corresponding to 5 to 10 credits. The modules of the research phase in the Master's degree programme in particular require a workload that exceeds this standard scope.

The **final grade is** calculated as the weighted average of the examination grades with the credit points of the modules .

You can find out which modules you have to take in your degree programme in the examination regulations for your degree programme.

Registration and conduct of the examinations:

Registration for each examination must be submitted to the Examinations Office within a set registration period. If a student fails an examination, he or she has the option of retaking it twice. Exceptions to this are the Bachelor's and Master's theses. They may be repeated once with a different topic.

The registration and examination dates can be found in your examination regulations.

In the following sections you will find, among other things, concrete **study plans**. Please note that these study plans are only **suggestions for** organising your studies. They are by no means prescribed. However, when planning your personal schedule, please note that some of the basic lectures build on each other and should therefore be listened to in the order given. If you have any questions, the study programme coordination and the subject advisors will be happy to help you.

Sample study plan

<table>
<tr><th>Semester/area</th><th colspan="2">Semester 1</th><th colspan="2">Semester 2</th><th>3. se.</th><th>4. se.</th><th>LP</th></tr>
<tr><td>Physics compulsory</td><td colspan="2">Quantum Optics + Advanced Solid State Physics</td><td colspan="2"></td><td></td><td></td><td>10</td></tr>
<tr><td>Physics elective</td><td colspan="4">QuantumFrontiers near events (non-classical matter wave metrology, non-classical light, theoretical atomic optics, optical frequency metrology, etc.).</td><td></td><td></td><td>15</td></tr>
<tr><td>ET Elective</td><td colspan="4">Courses from Electrical Engineering (TUBS) or Electronic Metrology in the Optics Laboratory</td><td></td><td></td><td>15</td></tr>
<tr><td rowspan="2">Internship</td><td colspan="4">Computational Methods, Simulations & Experimental Control</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">5</td></tr>
<tr><td>2 weeks: Data Analysis</td><td>2 weeks: Microcontroller/FPGA</td><td>2 weeks: QuTiP</td><td>2 weeks: ARTIQ</td></tr>
<tr><td>Project work</td><td colspan="4">Project work or (quantum) industrial internship</td><td></td><td></td><td>8</td></tr>
<tr><td>Seminar</td><td colspan="4">Seminar</td><td></td><td></td><td>3</td></tr>
<tr><td>Key competences</td><td colspan="6">Course from the offer of the LLC, LUIS; ZQS or the faculty</td><td>4</td></tr>
<tr><td>Master thesis</td><td colspan="2"></td><td colspan="2"></td><td colspan="2">Master's thesis Research internship/ Project planning</td><td>60</td></tr>
<tr><td></td><td colspan="2">30</td><td colspan="2">30</td><td>30</td><td>30</td><td>120</td></tr>
</table>

Focus of interest quantum communication (e.g. start WiSe)

Semester/area	Semester 1	Semester 2	3. se.	4. se.	LP
Physics Compulsory (LUH)	Quantum Optics **+** Advanced Solid State Physics				10
Physics Elective (LUH)	Single Photon Sources (from winter semester 2023/24)	Quantum Structure Devices **+** Nonlinear Optics			15
ET Elective (TUBS)	Optical communications engineering **+** information theory	Optoelectronics			15
Internship (LUH)	Computational Methods, Simulations & Experimental Control				5
	2 weeks: Data Analysis / 2 weeks: Microcontroller/FPGA	2 weeks: QuTiP / 2 weeks: ARTIQ			
Project work	Project work or (quantum) industrial internship				8
Seminar (LUH)	Integrated quantum optics **or** Solid state quantum technology, quantum information, and single photon emitter **or** Integrated Quantum Systems and Quantum Technologies				3
Key competences (LUH)		Course from the offer of the LLC, LUIS; ZQS or the faculty			4
Master thesis			Master's thesis Research internship/ Project planning		60
	30	30	30	30	**120**

Focus of interest quantum computing and simulation (e.g. start WiSe)

Semester/area	Semester 1	Semester 2	3. se.	4. se.	LP
Physics Compulsory (LUH)	Quantum Optics **+** Advanced Solid State Physics				10
Physics Elective (LUH)	Advanced Computational Physics	Quantum Computing **+** Quantum Dynamics and Theoretical Quantum Optics			15
ET Elective (TUBS)	Integrated circuits	Assembly and interconnection technology in electronics **+** nanoelectronics			15
Internship (LUH)	Computational Methods, Simulations & Experimental Control 2 weeks: Data Analysis 2 weeks: Microcontroller/FPGA 2 weeks: QuTiP 2 weeks: ARTIQ				5
Project work	Project work or (quantum) industrial internship				8
Seminar (LUH)	Quantum Optics meets Quantum Information **or Quantum** Information Theory **or** Technology Assessment for Quantum Computers and Quantum Technology				3
Key competences (LUH)	Course from the offer of the LLC, LUIS; ZQS or the faculty				4
Master thesis			Master's thesis Research internship/ Project planning		60
	30	30	30	30	**120**

Focus of interest Quantum Metrology and Sensors with Light
(e.g. start WiSe)

Semester/area	Semester 1	Semester 2	3. se.	4. se.	LP
Physics Compulsory (LUH)	Quantum Optics **+** Advanced Solid State Physics				10
Physics Elective (LUH)	Optical experiments and their control	Non-classical light & non-classical laser interferometry **+** non-linear optics			15
ET Elective (TUBS)	Advanced Electronic Devices	Optoelectronics **+** Fundamentals of Digital Signal Processing			15
Internship (LUH)	Computational Methods, Simulations & Experimental Control 2 weeks: Data Analysis | 2 weeks: Microcontroller/FPGA	2 weeks: QuTiP | 2 weeks: ARTIQ			5
Project work	Project work or (quantum) industrial internship				8
Seminar (LUH)	Optical components **or** Quantum Optics meets Quantum Information				3
Key competences (LUH)	Course from the offer of the LLC, LUIS; ZQS or the faculty				4
Master thesis			Master's thesis Research internship/ Project planning		60
	30	30	30	30	**120**

Focus of interest Quantum metrology and sensing with atoms
(e.g. start WiSe)

<table>
<tr><th>Semester/area</th><th colspan="2">Semester 1</th><th colspan="2">Semester 2</th><th>3. se.</th><th>4. se.</th><th>LP</th></tr>
<tr><td>Physics Compulsory (LUH)</td><td colspan="2">Quantum Optics + Advanced Solid State Physics</td><td colspan="2"></td><td></td><td></td><td>10</td></tr>
<tr><td>Physics Elective (LUH)</td><td colspan="2">Quantum sensor technology</td><td colspan="2">Non-classical atomic optics + non-linear optics</td><td></td><td></td><td>15</td></tr>
<tr><td>ET Elective (TUBS)</td><td colspan="2">Digital circuits</td><td colspan="2">Optoelectronics + Assembly and connection technology in electronics</td><td></td><td></td><td>15</td></tr>
<tr><td rowspan="2">Internship (LUH)</td><td colspan="4">Computational Methods, Simulations & Experimental Control</td><td rowspan="2"></td><td rowspan="2"></td><td rowspan="2">5</td></tr>
<tr><td>2 weeks: Data Analysis</td><td>2 weeks: Microcontroller/FPGA</td><td>2 weeks: QuTiP</td><td>2 weeks: ARTIQ</td></tr>
<tr><td>Project work</td><td colspan="4">Project work or (quantum) industrial internship</td><td></td><td></td><td>8</td></tr>
<tr><td>Seminar (LUH)</td><td colspan="4">Quantum logic with trapped ions or Advanced methods of quantum sensing or Modern experiments in atomic physics and quantum optics</td><td></td><td></td><td>3</td></tr>
<tr><td>Key competences (LUH)</td><td></td><td colspan="5">Course from the offer of the LLC, LUIS; ZQS or the faculty</td><td>4</td></tr>
<tr><td>Master thesis</td><td colspan="2"></td><td colspan="2"></td><td colspan="2">Master's thesis Research internship/ Project planning</td><td>60</td></tr>
<tr><td></td><td colspan="2">30</td><td colspan="2">30</td><td>30</td><td>30</td><td>120</td></tr>
</table>

Compulsory modules
Basics

Quantum optics		**Identification number/test code** ---
Master Quantum Engineering		**Module type** Mandatory
Credit points 5	**Frequency of the offer** WiSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1	**Module duration** 1 semester
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module M. Sc. Physics		

1	**Qualification goals** Students understand the basic concepts of quantum optics and can apply them independently to selected problems. They know advanced experimental methods of the field and can apply them under guidance.
2	**Contents of the module** - Quantisation of the EM field - Quantum states of the EM field (Fock, Glauber, squeezed states) - Heisenberg uncertainty relation (number/phase, amplitude/phase quadrature) - Photon statistics, quantum noise - Bell's inequality and non-locality - Squeezing and Entanglement Generation - Spontaneous emission, Lamb shift, Casimir effects - Atom-field interaction with coherent fields, dressed states - Photon scattering, Feyman graphs - Multiphoton processes - Quantum theory of non-linear susceptibility - Experiments in modern quantum optics
3	**Forms of teaching and courses** Lecture "Quantum Optics", 3 SWS Exercise "Quantum Optics", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Coherent optics
5	**Requirements for the award of credit points**
	Study achievements: Exercises
	Examination achievements: 30 min oral exam or 90-120 min written exam
6	**Literature** . Mandel/Wolf, Optical Coherence and Quantum Optics, Cambridge University Press . Walls/Milburn, Quantum Optics, Springer . Bachor/Ralph, A Guide to experiments in Quantum Optics, Wiley-VCH . Schleich, Quantum Optics in Phase space, Wiley-VCH

	Original literature
7	**Further information** ---
8	**Organisational unit** Institute for Quantum Optics (IQO), LUH
9	**Person responsible for the module** Prof. Dr. Piet O. Schmidt

Advanced solid state physics		**Identification number/test code**
Master Quantum Engineering		**Module type** Mandatory
Credit points 5	**Frequency of the offer** WiSe/SoSe	**Language** English
Area of competence ---	**Recommended semester** Semester 1	**Module duration** 1 semester
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module M. Sc. Physics		

1	**Qualification goals** Students acquire in-depth knowledge of theoretical models and experimental results in solid state physics. They are able to classify selected phenomena and develop models at their level of understanding. They become familiar with important developments in the field that have occurred in recent decades and have a clear impression of current unsolved problems in solid state physics. The students are able to assess the advantages and disadvantages of certain experimental techniques and acquire knowledge about the complementarity of different experimental possibilities.
2	**Contents of the module** - Dielectric properties - Quantum optics in solids - Magnetism - Superconductivity - New topics in solid state physics (phase transitions, low-dimensional systems, quantum computing, topological states)
3	**Forms of teaching and courses** Lecture "Advanced Solid State Physics", 3 SWS Exercise "Advanced Solid State Physics", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Introduction to Solid State Physics
5	**Requirements for the award of credit points**
	Study achievements: Tests
	Examination achievements: Oral exam or written exam 90 min
6	**Literature** R. Gross and A. Marx, Solid State Physics, De Gruyter

	. D. Snoke, Solid State Physics: Fundamental Concepts, Cambridge University Press
7	**Further information** ---
8	**Organisational unit** Institute for Solid State Physics (FKP), LUH
9	**Person responsible for the module** Prof. Dr Fei Ding

Seminar		**Identification number/test code**
Master Quantum Engineering		**Module type** Mandatory
Credit points 3 LP / 2 SWS	**Frequency of the offer** WiSe/SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 90 h	Of which attendance time: 30 h	Of which self-study: 60 h
Further use of the module		

1	**Qualification goals** The students are able to independently research literature on a given, current topic from the field of quantum engineering, some of which is still the subject of research. Students are able to independently acquire a current field of knowledge. The students can structure and deliver a lecture on a complex topic of modern physics so that a physically educated audience can follow the lecture well. By structuring the lecture, they can also interest the audience in a complex special topic. The students are able to create an appealing presentation. (PowerPoint or similar). The students are able to lead a scientific discussion (about their own topic as well as about the topics of the other seminar participants). The students master the German or English technical language in free speech. Achieving the competence goals requires continuous participation.
2	**Contents of the module** - Advanced topics in physics
3	**Forms of teaching and courses** Courses from the offerings of the Leibniz Language Centre or the Centre for Key Competencies and correspondingly designated offerings of the faculties as well as computer courses from the offerings of the Computer Centre.
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: VbP (seminar performance)
6	**Literature** will be announced in the courses
7	**Further information** ---
8	**Organisational unit** Faculty of Mathematics and Physics
9	**Person responsible for the module**

	Dean of Studies

Key competences		**Identification number/test code**
Master Quantum Engineering		**Module type** Mandatory
Credit points 4 LP / 3 SWS	**Frequency of the offer** WiSe/SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 120 h	Of which attendance time: 42 h	Thereof self-study: 78 h
Further use of the module		

1	**Qualification goals** They learn and master exemplary key competences in the field of the chosen course.
2	**Contents of the module** - Content depending on the chosen course
3	**Forms of teaching and courses** Courses from the Leibniz Language Learning Centre or the Centre for Key Competences and correspondingly designated courses offered by the faculties, as well as computer courses from the Leibniz Universität IT Services (LUIS).
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: according to §6 of the examination regulations
	Examination achievements: -
6	**Literature**
7	**Further information** ---
8	**Organisational unit** Faculty of Mathematics and Physics
9	**Person responsible for the module** Dean of Studies

Practical application

Computational Methods, Simulations & Experimental Control		**Identification number/test code**
Master Quantum Engineering		**Module type** Mandatory
Credit points 5	**Frequency of the offer** WiSe/SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 and Semester 2	**Module duration** 8 weeks over 2 semesters
Student workload Total: 150 h	Of which attendance time: 30 h	Of which self-study: 120 h
Further use of the module		

1	**Qualification goals** The students learn simulated experimental and numerical methods, apply them themselves and develop model concepts to explain the experimental and numerical results. They know the function and programming of complex microelectronic components and development environments and can use them correctly for both experiment control and measurement data acquisition in real-time environments.
2	**Contents of the module** • Advanced data analysis • Microcontroller and FPGA programming • Quantum optics simulations with QuTiP • Real-time experiment control with ARTIQ
3	**Forms of teaching and courses** Practical course, 4 SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: Exercises
	Examination achievements: -
6	**Literature**
7	**Further information** ---
8	**Organisational unit** Institute for Quantum Optics (IQO), Institute for Solid State Physics (FKP), Institute for Gravitational Physics (IGP), LUH
9	**Person responsible for the module** Prof. Dr. Piet O. Schmidt

Elective modules
Practical application

Project work		Identification number/test code
Master Quantum Engineering		**Module type** Elective
Credit points 8 LP / 6 SWS	**Frequency of the offer** WiSe/SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 2	**Module duration** 8 weeks
Student workload Total: 320 h	Of which attendance time: -	Of which self-study: 220 h
Further use of the module		

1	**Qualification goals** The students are familiar with typical fields of activity and responsibilities of graduates in the field of quantum engineering in research. They can integrate themselves into a working environment with scientists and engineers from related disciplines and actively contribute in a team. They are familiar with examples of the further development of scientific findings in a research environment and understand the tasks that arise in this context.
2	**Contents of the module** Project work in a research group at a university or non-university research institution. The project work should be carried out in a typical research environment of a quantum engineer. If possible, a defined (small) research project should be worked on as part of the project work. The length is at least eight weeks.
3	**Forms of teaching and courses** ---
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: VbP or PJ - written elaboration of the project work (10-15 pages)
6	**Literature** Current literature on the respective scientific problem
7	**Further information** The internship is subject to prior approval by the chairperson of the examination board.
8	**Organisational unit** Versch. Faculties
9	**Person responsible for the module** Dean of Studies

Quantum Industry Practicum A/B		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 8 or 13 LP / 6 or 10 SWS	**Frequency of the offer** WiSe/SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 2	**Module duration** 8 o.12 weeks
Student workload Total: 320 h o. 480 h	Of which attendance time: -	Of which self-study: 320 h o. 480h
Further use of the module		

1	**Qualification goals** The students are familiar with typical fields of tasks and areas of activity of graduates in the field of quantum engineering in professional practice. They can integrate themselves into a working environment with scientists and engineers from related disciplines and actively contribute in a team. They are familiar with examples of the implementation of scientific findings in an industrial process and understand the tasks that arise in this context.
2	**Contents of the module** Internship in an industrial company. University institutes are excluded; in exceptional cases, the internship can also take place in a non-university research institution. The internship should be carried out in a typical professional field of a quantum engineer. If possible, a defined (small) project should be worked on during the internship.
3	**Forms of teaching and courses** Internship
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: VbP (internship report (10-15 pages))
6	**Literature**
7	**Further information** *Quantum industrial internship variant B:* 8 weeks are planned for the duration of the industrial internship, which are remunerated with 8 LP. *Quantum industrial placement variant A:* If the industrial placement is extended to 12 weeks, an additional 5 LP are awarded. Instead, one less compulsory elective module must be taken. If the industrial internship is extended more, no more LPs can be awarded for it.
8	**Organisational unit** QUEST LFS, LUH
9	**Person responsible for the module** Vice Chairperson QUEST-LFS

Quantum range (LUH)

Introduction to Nanophysics		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module		

1	**Qualification goals** The students acquire competences suitable for the development of nanostructures. The students learn experimental methods for the production and improvement of nanostructures and how to apply them.
2	**Contents of the module** - Fabrication of nanostructures by lithography and self-organisation - Electronic structure, interface states - Quantum size effects - Transport signatures in mesoscopic systems - Magnetoresistance effects - Quantum Hall effect, e.g. in graphene - Instabilities of 1-dimensional structures - Single electron transistors - Molecular electronics - Experimental methods
3	**Forms of teaching and courses** Lecture "Physics in Nanostructures", 2 SWS Exercise "Physics in Nanostructures", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Introduction to solid state physics, surface physics
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: Oral exam 30 min or written exam 90-120 min
6	**Literature** . Ivan V Markov, Crytsal Growth for Beginners, (World Scientific) . Thomas Heinzel, Mesoscopic Electronics in Solid State Nanostructure, (Wiley) . Philip Hofmann, Surface Science: An Introduction, (kindle.edition) . Rainer Waser, Nanoelectronics and Information Technology, (Wiley)
7	**Further information** ---
8	**Organisational unit** Institute for Solid State Physics (FKP)

9	**Person responsible for the module** Prof. Dr Fei Ding

Quantum structure devices		Identification number/test code
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module		

1	**Qualification goals** After completing the module, students have a deeper understanding of quantum mechanical phenomena in semiconductor devices. They possess the ability to design and create semiconductor quantum structures. dimension.
2	**Contents of the module** - Quantum effects in semiconductor structures - Physics of two-dimensional electron gases - Quantum wires - Quantum dots - Coherence and interaction effects - Single electron tunnel transistor - Quantum computing
3	**Forms of teaching and courses** Lecture "Quantum Structure Devices", 3 SWS Exercise "Quantum Structure Devices", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Introduction to Solid State Physics, Advanced Solid State Physics
5	**Requirements for the award of credit points**
	Study achievements: Exercises
	Examination achievements: 30 min oral exam or 90-120 min written exam
6	**Literature** . C. Weisbuch, B. Vinter, Quantum Semiconductor Structures, Academic Pr Inc . S.M. Sze, Semiconductor Devices: Physics and Technology, Wiley . M.J. Kelly, Low-Dimensional Semiconductors: Materials, Physics, Technology, Devices, Oxford University Press
7	**Further information** ---
8	**Organisational unit** Institute for Solid State Physics (FKP), LUH
9	**Person responsible for the module** Management FKP

Quantum sensor technology		Identification number/test code
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** WiSe / SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module		

1	**Qualification goals** Students understand the basic concepts of quantum sensors such as optical clocks and matter wave interferometers, as well as their characterisation. They know advanced experimental methods of the field and can apply them under guidance. They are familiar with applications of optical clocks and matter wave interferometers and can evaluate them independently and competently.
2	**Contents of the module** • Atom-light interaction • Trapped ions, atoms in optical lattices • Components of an optical clock and clock operation • Systematic effects and their suppression; examples of optical clocks • Optical frequency combs and frequency distribution • Statistical uncertainty of clocks • Applications and future developments: Fundamental physics, geodesy, multi-ion clocks, entanglement • Diffraction of atoms and molecules at material lattices and slits • Atom interferometry with laser beam splitters • Path integrals, propagators and phase shift calculation • Acceleration and rotation detection with atomic interferometry • Matter wave diffraction in the different regimes • Interferometry Bose-Einstein condensates • Optical gratings and large pulse transfer • Atomic interferometry with extended time (fountains, microgravity, space missions) • Fundamental tests and detection of gravitational waves with atomic sensors • Atomic interferometry with non-classical states of matter (squeezed sources)
3	**Forms of teaching and courses** Lecture: "Optical Clocks", 2 SWS Lecture: "Matter-Wave Interferometry", 2 SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**

	Study achievements: -
	Examination achievements: Oral exam 30 min or written exam 90-120 min
6	**Literature**
7	**Further information** ---
8	**Organisational unit** Institute for Quantum Optics (IQO), LUH
9	**Person responsible for the module** Prof. Dr. Piet O. Schmidt, Prof. Dr. Ernst Maria Rasel

Nonlinear optics		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module		

1	**Qualification goals** The students are able to understand modifications of the optical properties of a material under the influence of light and to modify the optical properties of a material independently. The aim of the module is to investigate frequency-converted processes and to be able to understand their application in science and technology.
2	**Contents of the module** - Nonlinear optical susceptibility - Crystal optics, tensor optics - Wave equation with non-linear source terms - Frequency doubling, sum, difference frequency generation - Optical parametric amplifier, oscillator - Phase matching schemes, quasi-phase matching - Electro-optical effect - Electro-acoustic modulator - Frequency tripling, Kerr effect, self-phase modulation, self-focusing - Raman, Brillouin scattering, four-wave mixing - Nonlinear propagation, solitons
3	**Forms of teaching and courses** Lecture "Nonlinear Optics", 3 SWS Exercise "Nonlinear Optics", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Atomic and molecular physics
5	**Requirements for the award of credit points**
	Study achievements: Exercises

	Examination achievements: Oral exam 30 min or written exam 90-120 min
6	**Literature** - Agrawal, Nonlinear Fiber optics, Academic Press - Boyd, Nonlinear Optics, Academic Press - Shen, Nonlinear Optics, Wiley-Interscience - Dmitriev, Handbook of nonlinear crystals, Springer - Original literature
7	**Further information** ---
8	**Organisational unit** Institute for Quantum Optics (IQO), LUH
9	**Person responsible for the module** Prof. Dr. Uwe Morgner

Photonics

Photonics		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** WiSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module		

1	**Qualification goals** After completing the module, students know the essential basics of modern photonics and can apply this knowledge to the assessment, design and simulation of photonic systems.
2	**Contents of the module** - Waves in matter - Dielectric waveguides (planar, glass fibre), integrated waveguides - Photonic crystals - Waveguide - Modes - Nonlinear fibre optics - Fibre optic components (circulators, AWG, fibre Bragg gratings, modulators) - Fibre laser - Laser diodes, photodetectors - Optical communications technology (RZ, NRZ, WDM/TDM) - Networks
3	**Forms of teaching and courses** Lecture "Photonics", 2 SWS Exercise "Photonics", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Coherent optics, non-linear optics
5	**Requirements for the award of credit points**
	Study achievements: Exercises

	Examination achievements: Oral exam 30 min or written exam 90-120 min
6	**Literature** - Reider, Photonics, Springer - Menzel, Photonics, Springer - Agrawal, Nonlinear Fiber optics, Academic Press - Original literature
7	**Further information** ---
8	**Organisational unit** Institute for Quantum Optics (IQO), LUH
9	**Person responsible for the module** Prof. Dr Boris Chichkov

Atom optics		Identification number/test code
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module		

1	**Qualification goals** The lecture gives an insight into modern experimental physics with cold atomic gases. This field has become one of the most active areas of atomic and molecular physics in recent years. The aim is for students to master the methods of laser cooling and the storage of atoms in traps, which enable spectroscopic precision measurements and, in particular, the development of very accurate atomic clocks.
2	**Contents of the module** - Atom-light interaction - radiation pressure forces - Atomic and ion traps - Cooling through evaporation - Bose-Einstein condensation - Ultracold Fermi gases - Experiments with ultracold and degenerate quantum gases - Atoms in optical periodic lattices - Atomic interferometry and frequency standards
3	**Forms of teaching and courses** Lecture "Atom Optics", 2 SWS Exercise "Atom Optics", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Atomic and molecular physics, quantum optics
5	**Requirements for the award of credit points**
	Study achievements: Exercises
	Examination achievements: Oral exam 30 min or written exam 90-120 min
6	**Literature** B. Bransden, C. Joachain, Physics of Atoms and Molecules, Longman 1983 R. Loudon, The Quantum Theory of Light, OUP, 1973 Current publications
7	**Further information** ---
8	**Organisational unit** Institute for Quantum Optics (IQO), LUH
9	**Person responsible for the module** Prof. Dr Silke Ospelkaus-Schwarzer

Non-classical atom optics		Identification number/test code
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module		

1	**Qualification goals** The students acquire knowledge about the generation of a Bose-Einstein condensate. You can use your knowledge in the development of high-precision sensors, but also to investigate fundamental physical effects.
2	**Contents of the module** - Generation of ultracold atoms - Many-particle quantum systems - Description and visualisation of atomic many-body states - Entanglement - Interferometry and fundamental limits - Overview of current experimental realisations - Central research results of recent years
3	**Forms of teaching and courses** Lecture "Non-Classical Atomic Optics", 2 SWS Exercise "Non-Classical Atomic Optics", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Atomic and molecular physics, quantum optics
5	**Requirements for the award of credit points**
	Study achievements: Exercises
	Examination achievements: Oral exam 30 min or written exam 90-120 min
6	**Literature** . C. C. Gerry and P.L. Knight, Introductory Quantum Optics, University Press, Cambridge (2005). . Pezzè et al, Quantum metrology with nonclassical states of atomic ensembles, Rev. Mod. Phys. 90, 035005 (2018). . Current publications
7	**Further information** ---
8	**Organisational unit** Institute for Quantum Optics (IQO), LUH
9	**Person responsible for the module** Prof. Dr. Carsten Klempt

Experimental Atomic Physics		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** WiSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module		

1	**Qualification goals** After successful completion of the module, students are able to apply experimental methods of atomic physics and quantum sensing to 1. in original literature 2. describe them on a theoretical basis 3. and their practical implementation in current experiments or plan them themselves.
2	**Contents of the module** The aim of the lecture is to gain an overview of the variety of experimental methods in modern atomic physics. The required theoretical basics are introduced in the lecture. In the exercise groups, the topics covered are deepened on the basis of historical and current publications, with a special focus on the understanding of experimental techniques. Topics covered include fundamentals of atom-light interaction, laser cooling methods and techniques for the production of Bose-Einstein condensates. The lecture then covers methods for implementing quantum sensors, particularly with regard to noise and systematic effects. Through affiliated laboratory tours at the Institute of Quantum Optics, the students get a direct insight into typical experimental setups. The lecture thus also serves as content preparation for a subsequent Master's thesis in the field of experimental atomic physics.
3	**Forms of teaching and courses** Lecture "Experimental Methods in Atomic Physics", 2 SWS Exercise "Experimental Methods in Atomic Physics", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Atomic and molecular physics, coherent optics
5	**Requirements for the award of credit points**
	Study achievements: Participation in exercise/presentation/solution of exercise sheets
	Examination achievements: Oral exam 30 min or written exam
6	**Literature** . T. Mayer-Kuckuck, Atomic Physics, Teubner, 1994 . B. Bransden, C. Joachain, Physics of Atoms and Molecules, Longman 1983 . H. Haken, H. Wolf, Atomic and Quantum Physics as well as Molecular Physics and Quantum Chemistry, Springer . H. Metcalf, P. van der Straaten, Laser Cooling and Trapping, Springer 1999 . F. Riehle, Frequency Standards, Wiley 2004

7	**Further information** ---
8	**Organisational unit** Institute for Quantum Optics (IQO), LUH
9	**Person responsible for the module** Prof. Dr Ernst Maria Rasel

Computational Photonics		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 6	**Frequency of the offer** SoSe	**Language** English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 150h	Of which attendance time: 56 h	Thereof self-study: 94 h
Further use of the module		

1	**Qualification goals** The module teaches basic skills of software development for problems of computer-oriented physics and deepens specific techniques for the numerical solution of problems in optics. In addition, it serves as an overview of general aspects of modern optics. After successful completion of the module, students are able to • understand problems in modern and non-linear optics • apply principles of numerical modelling and implementation • Implement software development methods • solve problems in computer-oriented photonics independently
2	**Contents of the module** The lecture is divided into two parallel tracks: Fundamentals of Photonics and Numerical Methods. The course includes a practical exercise that gives students basic experience with computer simulations. Subject content: • Interaction z between light and matter (chromatic and geometric dispersion, second and third order susceptibility, Raman scattering, supercontinuum generation, multiphoton and tunnel ionisation, low order harmonic radiation). • Light transport in turbid media • Photoacoustics • Matrix optics • Pulse propagation equations • Atoms in strong optical fields (Schrödinger equation for atoms, higher-harmonic generation, Brunel/THz radiation, attosecond optics). • Computer modelling methods in electromagnetics (time domain solvers, frequency domain methods, finite element methods). • Monte Carlo method • Spectral and pseudo-spectral methods • Runge-Kutta and operator splitting methods • Parallel Computing (openMP, openMPI)
3	**Forms of teaching and courses** Lecture "Computational Photonics", 2 SWS Exercise "Computational Photonics", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Experience with the computer and basics of programming.

5	**Requirements for the award of credit points**
	Study achievements: Participation in the lecture and in the practical exercises
	Examination achievements: The grade results from 40% of the assessment of the performance in the computer exercises and 60% of the exam grade.
6	**Literature** . S. Obayya, Computational Photonics, John Wiley & Sons, 2011 . oachain, Kylstra, Potvliege: Atoms in Intense Laser fields . Lux/Koblinger: Monte Carlo Particle Transport Methods: Neutron and Photon Calculations
7	**Further information** ---
8	**Organisational unit** Institute for Quantum Optics (IQO), LUH
9	**Person responsible for the module** Prof. Dr Ayhan Demircan

Non-classical light and non-classical laser interferometry		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** WiSe/SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 and Semester 2	**Module duration** 2 semesters
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module		

1	**Qualification goals** The students acquire competences beyond Quantum Optics I on the topic of non-classical light, in particular squeezed states, and non-classical laser interferometry, which include measurements with accuracies below the quantum limit of interferometry, among others in interferometric gravitational wave detection.
2	**Contents of the module** - Classical and non-classical states of light - Criteria for "non-classicality - Detection and generation of jib states - Detection and generation of squeezed light - Quantum state tomography - EPR-entangled (two-mode squeezed) light - Optical test of non-locality - Shot noise and radiation pressure noise in the interferometer - Square operators and "input-output" relations of interferometers - The standard quantum limit of position measurement - "Quantum nondemolition" techniques - Interferometer with squeezed light and other non-classical states of light - Opto-mechanical coupling and optical springs - Quantum states of mechanical oscillators - Cooling mechanical oscillators to their quantum mechanical ground state - Interlacing mirrors and light
3	**Forms of teaching and courses** Lecture: "Non-Classical Light", 2 SWS Lecture: "Non-Classical Laser Interferometry", 2 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Coherent Optics, Nonlinear Optics, Nonclassical Light, Quantum Optics
5	**Requirements for the award of credit points**
	Study achievements: none
	Examination achievements: Oral examination or written exam
6	**Literature** . C.C. Gerry and P.L. Knight, Introductory Quantum Optics, University Press, Cambridge (2005). . H.-A. Bachor and T.C. Ralph, A guide to experiments in quantum optics,

	Wiley, 2nd edition (2003). . P. Saulson, Fundamentals of Interferometric GW detectors, World Scientific Pub Co Inc. . Original literature (scientific publications, primary literature)
7	**Further information** ---
8	**Organisational unit** Institute for Gravitational Physics (IGP), LUH
9	**Person responsible for the module** Prof. Dr Michèle Heurs

Optical experiments and their control		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** WiSe/SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 and Semester 2	**Module duration** 2 semesters
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module		

1	**Qualification goals** Students acquire competences necessary for working in a (quantum) optical laboratory. The competences are extended by corresponding theoretical basics and experimental knowledge and also cover useful technical content.
2	**Contents of the module** - Lasers and the cause of power, frequency and beam position fluctuations - Fundamentals of control engineering - Length control of interferometers and optical resonators - Detection of frequency fluctuations and their suppression - Detection of power fluctuations and their suppression - Beam position control - Electronics basics: Kirchhoff rules, impedance, phasor diagrams - Operational amplifiers: Functionality and basic circuits - Oscillating circuits and filters (active / passive) - Spectrum Analyser and Network Analyser - Measurement and interpretation of transfer functions - Fundamentals of control engineering - Photodetection - Sensors and actuators in optical experiments - Noise measurements
3	**Forms of teaching and courses** Lecture: "Laser stabilisation and control of optical experiments", 2 SWS Lecture: "Electronic metrology in the optics laboratory", 2 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Coherent optics
5	**Requirements for the award of credit points**
	Study achievements: Participation in the lecture; homework assignments
	Examination achievements: Oral examination or written exam
6	**Literature** . Horowitz & Hill, The Art of Electronics, Cambridge University Press . Abramovici & Chapsky, Feedback Control Systems, Kluwer Academic Publishers . Yariv, Quantum Electronics, Wiley . Siegman, Lasers, University Science Books . Original literature (scientific publications, primary literature)

7	**Further information** ---
8	**Organisational unit** Institute for Gravitational Physics (IGP), LUH
9	**Person responsible for the module** Prof. Dr Michèle Heurs, apl. Prof. Dr Benno Willke

Computational Physics		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 6	**Frequency of the offer** SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:180 h	Of which attendance time: 60 h	Of which self-study: 120 h
Further use of the module		

1	**Qualification goals** Students are able to program basic simulations of physical systems, visualisation of data and statistical data analysis.
2	**Contents of the module** - Basic numerical methods (differentiation, integration, interpolation, solution of a non-linear equation, systems of linear algebraic equations, Monte Carlo methods) - Numerical solution of common problems in physics (differential equations, eigenvalue problems, optimisation, integration and sums of many variables) - Applications from mechanics, electrodynamics, thermodynamics and quantum mechanics - Data analysis (statistical analysis, equalisation, extrapolation, spectral analysis) - Visualisation (graphical representation of data) - Introduction to the simulation of physical systems (dynamic systems, simple molecular dynamics) - Computer algebra
3	**Forms of teaching and courses** Lecture "Computational Physics", 2 SWS Exercise "Computational Physics", 2 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Experience with the computer and basics of programming, Analysis I+II, Theoretical Electrodynamics, Analytical Mechanics, Special Theory of Relativity, Introduction to Quantum Theory.
5	**Requirements for the award of credit points**
	Study achievements: Practical exercises
	Examination achievements: Oral exam 30 min and written exam 90-120 min
6	**Literature** . Wolfgang Kinzel and Georg Reents, "Physik per Computer", Spektrum Akademischer Verlag . S.E. Koonin and D.C. Meredith, "Computational Physics", Addison-Wesley . W.H. Press, S.A. Teukolsky, W.T. Vetterling, B.P. Flannery, "Numerical Recipes in C++", Cambridge University Press . J.M. Thijssen, "Computational Physics", Cambridge University Press . Tao Pang, "An Introduction to Computational Physics", Cambridge University

	Press . S. Brandt, "Data Analysis", Spektrum Akademischer Verlag . V. Blobel and E. Lohrmann, "Statistical and Numerical Methods of Data Analysis", Teubner Verlag . R.H. Landau, M.J. Paez, and C.C. Bordeianu, Computational Physics, Wiley-VCH, 2007
7	**Further information** ---
8	**Organisational unit** Institute for Theoretical Physics (ITP), LUH
9	**Person responsible for the module** Prof. Dr Eric Jeckelmann

Advanced Computational Physics		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 8	**Frequency of the offer** WiSe/SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 240 h	Of which attendance time: 90 h	Of which self-study: 150 h
Further use of the module		

1	**Qualification goals** Students are able to program complex simulations of physical systems, visualisation of data and statistical data analysis - among other things with the help of machine learning.
2	**Contents of the module** - Exact diagonalisation - Monte Carlo simulations - Numerical renormalisation group - density functional theory - Molecular dynamics - Quantum dynamics - Artificial intelligence and machine learning - Quantum computer
3	**Forms of teaching and courses** Lecture "Advanced Computational Physics", 4 SWS Exercise "Advanced Computational Physics", 2 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Introduction to Quantum Theory, Statistical Physics, Computational Physics".
5	**Requirements for the award of credit points**
	Study achievements: Practical exercises
	Examination achievements: Oral exam 45 min and written exam 90-120 min
6	**Literature** . J.M. Thijssen, Computational Physics (Cambridge University Press, 2007) . S.E. Koonin and D.C Meredith, Computational Physics, Addison-Wesley, 1990. . T. Pang, Computational Physics, Cambridge University Press, 2006 . H. Gould, J. Tobochnik, and W. Christian, Computer Simulation Methods, Pearson Education, 2007
7	**Further information** ---
8	**Organisational unit** Institute for Theoretical Physics (ITP), LUH
9	**Person responsible for the module** PD Dr Hendrik Weimer

Quantum Dynamics and Theoretical Quantum Optics		Identification number/test code
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** WiSe / SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module M. Sc. Physics		

1	**Qualification goals** After successful completion of the module, students are able to • quantise a field • characterise the quantum state of a field • understand the origins of dissipation and decoherence • Understand the second quantisation • Know how to derive and solve equations of motion for a simple system of light-matter interaction.
2	**Contents of the module** - Field quantisation, Casimir effect - Jib states, thermal states, coherent states - Phase space distributions (P-function, Husimi function, Wigner function) - Non-classical light - Atom-field interaction (perturbation theory, Rabi oscillations, Jaynes-Cummings model, Floquet theory, fluorescence, spontaneous emission) - Stochastic methods (master equation, Fokker-Planck equation), parametric amplification - Atomic optics, cavity QED, strong laser fields
3	**Forms of teaching and courses** Lecture "Theoretical Quantum Optics", 3 SWS Seminar "Quantum Dynamics", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Theoretical electrodynamics, introduction to quantum theory
5	**Requirements for the award of credit points**
	Study achievements: Practical exercises
	Examination achievements: Oral exam 30 min and written exam 90-120 min
6	**Literature** . C. Gerry and P. Knight, Introductory Quantum Optics, Cambridge University Press . S. Barnett, Methods in theoretical quantum optics, Clarendon Press . D. Walls and G. Milburn, Quantum Optics, Springer . H.-J. Kull, Laser Physics, Oldenbourg . W. Schleich, Quantum optics in phase space, Wiley-VCH . C. Joachain, N. Kylstra and R. Potvliege, Atoms in intense laser fields, Cambridge University Press

	. R. Loudon, The Quantum Theory of Light, Oxford Science Publications
7	**Further information** ---
8	**Organisational unit** Institute for Theoretical Physics (ITP), LUH
9	**Person responsible for the module** Prof. Dr Luis Santos

Quantum computing		Identification number/test code
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module		

1 Qualification goals

Upon successful completion of the programme, students will be able to,

1) To discuss the DiVincenzo criteria
2) Name one-two and three-qubit gates, represent them in truth tables and depict them as "quantum circuits".
3) Implement quantum algorithms in elementary gates
4) Describe elementary quantum algorithms (e.g. Grover, quantum Fourier transform).
5) To perform the formulation of algorithms in Qiskit
6) To give an overview of complexity classes of algorithms
7) Formulate the distinction between "circuit" based approaches and, for example, annealers.
8) Capture elementary quantum error correction algorithms
9) Discuss the error analysis and benchmarking of quantum gates
10) Discuss quantum computing with NISQ devices
11) Using suitable examples, understand the transition from a quantum physics problem to a simulation on a quantum computer.
12) To discuss the quantum CCD architecture for the ion trap quantum computer.
13) Discuss ion trap basics
14) Discuss light-matter interaction in the two-level system (Schrödinger equation and optical Bloch equations).
15) Capture the mode structure of Coulomb crystals and the treatment of quantised motion using the ladder operator formalism
16) Describe the implementation of one- and two-qubit gates
17) Capture current demonstration experiments on quantum algorithms on ion trap quantum computers (original literature).
18) Describe the basics of other architectures (especially superconductors).

2 Contents of the module

Fundamentals of quantum information processing, quantum algorithms and quantum computer programming. Implementation of quantum computers with stored ions: Memory concept, gate implementation, scaling, current original literature. Fundamentals of other quantum computing platforms.

3 Forms of teaching and courses

Lecture "Quantum Computing", 3 SWS
Tutorial on "Quantum Computing", 1 SWS

4a	**Participation requirements** ---
4b	**Recommendations** Quantum optics, theoretical quantum optics or atomic and molecular physics
5	**Requirements for the award of credit points**
	Study achievements: 50% of the points in the exercises, participation in the exercise group
	Examination achievements: Written exam 90-120 min or oral exam
6	**Literature** M.A. Nielsen and I. Chuang, "Quantum computation and quantum information", Cambridge University Press. J. Preskill, lecture notes "Quantum Computation", http://theory.caltech.edu/~preskill/ph229/ P.K. Ghosh, "Ion Traps", Oxford University Press D. J. Wineland et al, "Experimental Issues in Coherent Quantum-State Manipulation of Trapped Atomic Ions", J. Res. Natl. Inst. Stand. Technol. 103, 259 (1998) D. Leibfried et al, "Quantum Dynamics of Single Trapped Ions", Rev. Mod. Phys. 75, 281 (2003) R. Blatt and D. Wineland, "Entangled States of Trapped Atomic Ions", Nature 453, 1008 (2008). D.J. Wineland, Nobel Lecture: Superposition, Entanglement, and Raising Schrödinger's Cat, Rev. Mod. Phys. 85, 1103 (2013) C.D. Bruzewicz et al, "Trapped-Ion Quantum Computing: Progress and Challenges", Applied Physics Reviews 6, 021314 (2019).
7	**Further information** ---
8	**Organisational unit** Institute for Quantum Optics (IQO), Institute for Theoretical Physics (ITP), LUH
9	**Person responsible for the module** Prof. Dr. C. Ospelkaus, Prof. Dr. T. Osborne, Prof. Dr. K. Hammerer, Prof. Dr. L. Santos, Priv.-Doz. Dr. H. Weimer

Single Photon Sources - from basics to applications		Identification number/test code
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 150 h	Thereof attendance time:42 h	Thereof self-study: 108 h
Further use of the module		

1	**Qualification goals** The introduction of the photon by Einstein, together with the heroic endeavors of Bohr, Heisenberg, Schrödinger and many others, gave birth to quantum mechanics in the beginning of the last century. Though initially driven by curiosity, the introduced concepts have fueled many revolutionary applications, for example, quantum networking and quantum information processing. In this lecture you will learn the fundamentals of quantum networking and information processing with single photons, ranging from the single photon statistics up to the modern applications of single photon sources. A particular emphasis is given to the discussions of solid-state single photon sources, such as quantum dots, colour centres, and organic molecules. Their history, current progress and challenges are discussed. Together, we will discuss how the efficient single photon sources can reshape the future of quantum communication, computation and metrology.
2	**Contents of the module** -Quantum optics in a nutshell - a review -Photon statistics - basic concepts -Generation of single photons - current progress and challenges -Solid-state single photon emitters -Applications of single photon sources - quantum communication, computation and metrology
3	**Forms of teaching and courses** Lecture "Single Photon Sources", 3 SWS Exercise "Single Photon Sources", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Prior knowledge in quantum mechanics
5	**Requirements for the award of credit points**
	Study achievements: Exercise task, lectures
	Examination achievements: Written 9-120 min or oral 30 min exam
6	**Literature** Lecture notes of the lecturer; primary literature Artur Ekert - "Introduction to Quantum Information" Scott Aaronson - "Introduction to Quantum Information Science". Mark Fox - "Quantum optics: An introduction"

7	**Further information** ---
8	**Organisational unit** Institute for Solid State Physics (FKP), LUH
9	**Person responsible for the module** Prof. Dr Fei Ding and Prof. Dr Ilja Gerhardt

Applied photonic quantum technologies		Identification number/test code
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total: 150 h	Of which attendance time: 60 h	Of which self-study: 90 h
Further use of the module		

1	**Qualification goals**
	• Understand different approaches for photonic quantum systems
	• Know basic experimental techniques used to realize and characterize photonic quantum systems
	  ○ fabrication of photonic quantum devices
	  ○ experimental photonic setups
	  ○ general measurement and characterization techniques
	• Be proficient in basic concepts of QIP
	  ○ representation of information in qu(antum)bits
	  ○ manipulation and read-out of information stored in qubits
	• Understand the use in application scenarios
	  ○ know basic examples of quantum information processing
	  ○ know basic examples of quantum communications
	• Know principles of quantum-enhanced measurements

2	**Contents of the module** The content of the lecture will encompass the fundamentals of photonic quantum technologies and their applications in sensing systems, quantum communication devices and quantum operations. The lecture will start with quantum light characteristics, quantum implementations, and continue with quantum light sources, quantum light control and photonic gates, and to the end discuss the applications for entanglement creation and measurement, quantum teleportation, entanglement swapping, super-dense coding, quantum algorithms and quantum sensing.
3	**Forms of teaching and courses** Lecture " Applied photonic quantum technologies ", 3 SWS
4a	**Participation requirements** ---
4b	**Recommendations**
5	**Requirements for the award of credit points** *Study achievements:* - *Examination achievements:* Oral examination 30 min
6	**Literature** - Mark Fox, Quantum Optics: An Introduction, Oxford Univ. Press (2006) - Hans-A. Bachor and Timothy C. Ralph, A Guide to Experiments in Quantum Optics, Wiley 2004. - Leonard Mandel and Emil Wolf, Optical coherence and quantum optics,

	Cambridge Univ. Pres 1995.
7	**Further information** ---
8	**Organisational unit** Institute for Quantum Optics, LUH
9	**Person responsible for the module** Prof. Dr Michael Kues

Engineering Department **(TUBS)**

Optoelectronics		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:150 h	Of which attendance time: 42 h	Thereof self-study: 108 h
Further use of the module TUBS		

1	**Qualification goals** After completing the module, the students know the functioning and dimensioning procedures for components of integrated optics, in particular waveguides. They are able to apply this knowledge in the analysis of optoelectronic systems with regard to the components and waveguides used and to assess and optimise the relevant system and component characteristics.
2	**Contents of the module** - Propagation of electromagnetic waves in space and with guidance - Refraction, reflection, total reflection at dielectric interfaces - Waveguiding in film and strip waveguides, loss mechanisms - Molecular dynamics - Modes and their calculation - Field distributions for step and gradient profile - Analogies to quantum mechanics - Periodic structures for distributed feedback: DFB, DBR - Electro-optical effects, directional coupler
3	**Forms of teaching and courses** Lecture "Optoelectronics", 2 SWS Exercise "Optoelectronics", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: written examination 90 minutes or oral examination 30 minutes
6	**Literature** . K. J. Ebeling, Integrated Optoelectronics, Springer, ISBN 3540546553
7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute for High Frequency Technology, TUBS
9	**Person responsible for the module** Prof. Dr.-Ing. Wolfgang Kowalsky

Advanced Electronic Devices		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** WiSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:150 h	Of which attendance time: 42 h	Thereof self-study: 108 h
Further use of the module TUBS		

1 Qualification goals

Upon completion of the Advanced Electronic Devices module, students will possess
- a basic understanding of the most important electronic and optoelectronic components
- Advanced knowledge of non-ideal effects as well as special, modern construction elements

They are able to apply this knowledge in the analysis of (opto)electronic systems with regard to the components used and their special (non-linear) properties and to assess and optimise the relevant system and component characteristics.

2 Contents of the module

- The non-ideal p-n junction (recombination and generation, high injection, finite long path regions)
- Transistors (bipolar, junction FET, MOSFET, CMOS, scaling / short channel effects,
HEMT, SiGe)
- Optoelectronic components (LEDs, semiconductor lasers, photodiodes, solar cells)
- Spin and magnetoelectronics
- Micro- and Nanoelectromechanical Systems M/NEMS
- Bio- and Nanoelectronic Systems (Semiconductor Biosensors, Molecular Electronics)

3 Forms of teaching and courses

Lecture "Advanced Electronic Devices", 2 SWS
Exercise "Advanced Electronic Devices", 1 SWS

4a Participation requirements

4b Recommendations

---

5 Requirements for the award of credit points

Study achievements: -

Examination achievements:
Oral examination 30 minutes or written examination 90 minutes

6 Literature

- A. Schlachetzki, Semiconductor Electronics, Teubner (1990) ISBN: 3-519-03070-5
- S. M. Sze, K.K. Ng, Physics of Semiconductor Devices, 3rd Ed. (2007), Wiley, ISBN-13: 978-0470068328

7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute for Semiconductor Technology, TUBS
9	**Person responsible for the module** Prof. Dr.-Ing. Hergo-Heinrich Wehmann

Advanced Quantum Technologies for Engineers		Identification number/test code
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:150 h	Of which attendance time: 42 h	Thereof self-study: 108 h
Further use of the module TUBS		

1	**Qualification goals** Knowledge in the basic concepts of quantum physics, basic knowledge in quantum optics, quantum electronics, optoelectronics and laser physics, quantum statistics, spinelectronics as a basis for future applications of quantum technologies.
2	**Contents of the module** Concepts of quantum physics have been developed at the beginning of 20th century, and developed into a comprehensive foundation of physics. Quantum technologies are already used in applications today, like e.g. semiconductor devices, laser devices or satellite navigation. The quantum principles of the first generation of applications are based on the concepts of coherence. Potential technologies of the second generation of quantum technologies will extend towards the manipulation of single quantum objects and will use many particle systems and entanglement. In a joint statement on the importance and commercialization of quantum technologies, the German Academies of Sciences urgently suggest to merge quantum technologies and engineering education. This is the goal of the lecture Advanced quantum technologies for engineers. It lays out the basis for an understanding of quantum effects, dealing with the following topics: quantum physics as scientific theory, principles of quantum theory, quantum technologies of 1st and 2nd generation. Further information can be found in Perspectives of quantum technologies [joint statement of Leopoldina, acatech and Union of the German Academies of Sciences and Humanities, ISBN 978-3-80473343-5, online available].
3	**Forms of teaching and courses** Lecture "Advanced Quantum Technologies for Engineers", 2 SWS Exercise "Advanced Quantum Technologies for Engineers", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: written exam, 120 minutes or oral examination 30 minutes
6	**Literature** ---
7	**Further information** TUBS course, as required Hybrid

8	**Organisational unit** Institute for Semiconductor Technology, TUBS
9	**Person responsible for the module** Prof. Dr. rer. nat. habil. Andreas Waag

Structure and connection technology in electronics		Identification number/test code
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:150 h	Of which attendance time: 42 h	Thereof self-study: 108 h
Further use of the module TUBS		

1	**Qualification goals** After completion of the module Packaging and Interconnection Technology in Electronics, students will have - a basic understanding of the most important procedures for the construction and connection technology of electronic Components - the ability to select suitable processes for the assembly and joining technology in the manufacture of Semiconductor modules - In-depth knowledge and practical experience in the use, analysis and evaluation of methods of building and Connection technology
2	**Contents of the module** - Open Wiring, Bread Board, Printed Circuit Board - Thick film technology, substrates, screen printing and pastes, thin film technology, photolithography - Surface Mount Technology, components, package shapes, modern developments (TAB, BGA, Flip-Chip, CSP, MCM) - Power modules, special requirements - Cooling, basics and problem definition, air cooling, liquid cooling - Thermomechanical stresses and reliability, basics, examples - Soldering, bonding, wire bonding, direct copper bonding, low-temperature joining technology
3	**Forms of teaching and courses** Lecture "Aufbau und Verbindungstechnik in der Elektronik", 2 SWS Exercise "Aufbau und Verbindungstechnik in der Elektronik", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: oral examination 30 minutes
6	**Literature** . W. Scheel (Ed.): Baugruppentechnologie der Elektronik - Montage (Verlag Technik, Berlin; Eugen G. Lenze Verlag, Saulgau, 1997) ISBN: 3-341-01100-5 . H.-J. Hanke (ed.): Baugruppentechnologie der Elektronik Leiterplatten

	(Verlag Technik, Berlin, Saulgau, 1994) ISBN: 3-341-01097-1 . H.-J. Hanke (ed.): Baugruppentechnologie der Elektronik Hybridträger (Verlag Technik, Berlin, Saulgau, 1994) ISBN: 3-341-01099-8 . M. Wutz: Wärmeabfuhr in der Elektronik (Vieweg, Wiesbaden, 1991) ISBN: 3-528-06392-0
7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute for Semiconductor Technology, TUBS
9	**Person responsible for the module** Prof. Dr. rer. nat. Erwin Peiner

<table>
<tr><td colspan="2">Fundamentals of nanooptics</td><td>Identification number/test code</td></tr>
<tr><td colspan="2">Master Quantum Engineering</td><td>Module type
Elective</td></tr>
<tr><td>Credit points
5</td><td>Frequency of the offer
SoSe</td><td>Language
German / English</td></tr>
<tr><td>Area of competence
---</td><td>Recommended semester
Semester 1 or Semester 2</td><td>Module duration
1 semester</td></tr>
<tr><td colspan="3">Student workload</td></tr>
<tr><td>Total:150 h</td><td>Of which attendance time: 42 h</td><td>Thereof self-study: 108 h</td></tr>
<tr><td colspan="3">Further use of the module
TUBS</td></tr>
</table>

<table>
<tr><td>1</td><td>Qualification goals
The participants can qualitatively and quantitatively describe basic phenomena of light propagation (reflection, scattering, absorption, transmission) at interfaces and in homogeneous media.
Participants will be able to understand important basic elements of nano-optics, such as waveguides, optical gratings, photonic
crystals or metamaterials, name them, qualitatively discuss their properties and name areas of application.
The participants are able to identify the basic elements in complex optical systems and to determine their
describe the respective function.
The participants can name important processes of micro- and nanostructuring and explain how they work.
explain.
Participants will be able to calculate the wave equation in simple dielectric, metallic and hybrid nano-optic
systems analytically and semi-analytically and interpret the solutions.
Participants will be able to classify optical resonance phenomena in nano-optical systems and to assess their
name the essential properties.</td></tr>
<tr><td>2</td><td>Contents of the module
- Basic concepts (photonic crystals, plasmonics)
- Fabrication and characterisation (metrology) of nanostructures- power modules, special requirements
- Photonic nanomaterials / metamaterials / metasurfaces
- Optical nanoemitters and nanoantennas
- Active photonic elements</td></tr>
<tr><td>3</td><td>Forms of teaching and courses
Lecture "Fundamentals of Nanooptics", 2 SWS
Exercise "Fundamentals of Nanooptics", 1 SWS</td></tr>
<tr><td>4a</td><td>Participation requirements
---</td></tr>
<tr><td>4b</td><td>Recommendations
---</td></tr>
<tr><td rowspan="3">5</td><td>Requirements for the award of credit points</td></tr>
<tr><td>Study achievements: -</td></tr>
<tr><td>Examination achievements:
written examination 120 minutes or oral examination 30 minutes</td></tr>
<tr><td>6</td><td>Literature</td></tr>
</table>

	- Novotny, Hecht: Principles of nano-optics, Cambridge University Press 2016 - Prasad: Nanophotonics, John Wiley & Sons 2004 - Jahns, Helfert: Introduction to Micro- and Nanooptics, Wiley VCH 2012
7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute for Applied Physics, TUBS
9	**Person responsible for the module** Prof. Dr Stefanie Kroker

Integrated circuits		Identification number/test code
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** WiSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:150 h	Of which attendance time: 42 h	Thereof self-study: 108 h
Further use of the module TUBS		

1	**Qualification goals** After completing the module, the students are able to understand integrated circuits, their structure and mode of operation and to design simple integrated circuits themselves. Further focus is on the methods of nanotechnology. The module provides an overview of the operation, design and technology of microelectronics integrated electronic circuits.
2	**Contents of the module** - Introduction - Digital basic circuits - MOS and CMOS - Silicon wafer fabrication - MOSFET process technology - Nanolithography - Etching techniques and oxidation - Design automation, design rules and assembly techniques - Back End Technologies - Modern developments: Storage technologies
3	**Forms of teaching and courses** Lecture "Integrated Circuits", 2 SWS Exercise "Integrated Circuits", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: Lecture / Project work
	Examination achievements: oral examination 20 minutes
6	**Literature** . J.M.Rabaey, A.Chandrakasan, B. Nikolic, Digital Integrated Circuits Prentice Hall Electronics and VLSI Series, 2002 ISBN: 8120322576 . A. Schlachetzki, Integrierte Schaltungen, Teubner, 1978, (as a copy in the IHT) ISBN: 3-519-03070-5 . D. Widmann, H. Mader, H. Friedrich, Technologie Hochintegrierte Schaltungen, Springer,1996 ISBN:3540593578 . >W. Prost, Technology of III/V Semiconductors, Springer, 1997 ISBN: 3540628045

7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute for CMOS Design, TUBS
9	**Person responsible for the module** Prof. Dr.-Ing. Vadim Issakov

Nanoelectronics		Identification number/test code
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:150 h	Of which attendance time: 56 h	Thereof self-study: 94 h
Further use of the module TUBS		

1	**Qualification goals** After completing the module "Nanoelectronics", students have an overview of the fundamentals of quantum mechanics and its application to metallic, magnetic and superconducting devices with nanometre dimensions.
2	**Contents of the module** - Quantum mechanics Wave function, potentials, interaction - Magnetism - Superconductivity - Manufacturing process - Josephson contacts - SET components - Data storage - THz transistors - Quantum computing
3	**Forms of teaching and courses** Lecture "Nanoelectronics", 3 SWS Exercise "Nanoelectronics", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points** *Study achievements: -* *Examination achievements:* oral exam 30 minutes (written exam 120 minutes only with very large numbers of participants)
6	**Literature** . R. Waser, Nanoelectronics and Information Technology, Wiley-VCH, 2003, ISBN 978-3527403639 . M. Köhler, Nanotechnology, Wiley-VCH, 2007, ISBN 978-3527318711 . Jasprit Singh, Modern Physics for Engineers, Wiley, 1999, ISBN 978-0471330448 . N. Ashcroft, N. Mermin, Solid State Physics, Cengage Learning Services, 1976, ISBN 978-0030839931 . S. Flügge, Computational Methods of Quantum Theory, Springer Verlag 1993, ISBN 978-3540567769 . W. Nolting, Quantum Mechanics, Volume 5 from Grundkurs: Theoretische Physik, Springer-Verlag, 2007, ISBN 978-3540688686

7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute of Electrical Measurement and Fundamentals of Electrical Engineering, TUBS
9	**Person responsible for the module** Prof.Dr.rer.nat. Meinhard Schilling

Numerical analysis of radiation phenomena		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:150 h	Of which attendance time: 42 h	Thereof self-study: 108 h
Further use of the module TUBS		

1	**Qualification goals** After completing the module, the students are able to specify suitable numerical solution methods for problems in the field of electromagnetic radiation. The approaches underlying the methods are understood, as are the resulting limits in applicability and possible sources of error.
2	**Contents of the module** - Quantitative description of radiation phenomena by means of special numerical calculation methods - Theoretical concepts of established methods (FE, FD, MoM) and newer approaches (e.g. wavelets) - Criteria of bandwidth and complexity of boundary conditions - Suitability and application limits of the methods - Practical application examples from EMC (absorption in technical materials and biological tissue, shielding) and antenna development
3	**Forms of teaching and courses** Lecture "Numerical Analysis of Radiation Phenomena", 2 SWS Exercise "Numerical Analysis of Radiation Phenomena", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: Written exam 60 minutes or oral exam 30 minutes
6	**Literature** . Arnulf Kost, Numerische Methoden in der Berechnung elektromagnetischer Felder, Springer-Verlag, Berlin, 1994, ISBN 3-540-55005-4 . Matthew N.O. Sadiku, Numerical Techniques in Electromagnetics, CRC Press, Boca Raton, 2001, ISBN 0-8493-1395-3
7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute for Electromagnetic Compatibility, TUBS
9	**Person responsible for the module** Prof. Dr. rer. nat. Achim Enders

Optical communications engineering		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 6	**Frequency of the offer** WiSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:180 h	Of which attendance time: 56 h	Thereof self-study: 124 h
Further use of the module TUBS		

1	**Qualification goals** After completing the module, the students understand the mode of operation and know the performance characteristics of different components of optical transmission links. They can design and dimension fibre-optic transmission links.
2	**Contents of the module** - Semiconductor materials - Emission and absorption - Heterostructures, quantum films - Laser diodes - Optical amplifier - Optoelectronic modulators - photodetectors - Systems of optical communications engineering
3	**Forms of teaching and courses** Lecture "Optical Communications Engineering", 2 SWS Exercise "Optical Communications Engineering", 2 SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: Written exam 120 minutes or oral exam 30 minutes
6	**Literature** . S. L. Chuang, Physics of Photonic Devices, Wiley & Sons, ISBN 9780470293195
7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute for High Frequency Technology, TUBS
9	**Person responsible for the module** Prof. Dr Thomas Schneider

THz systems engineering / THz photonics		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** WiSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:150 h	Of which attendance time: 56 h	Thereof self-study: 94 h
Further use of the module TUBS		

1	**Qualification goals** After completing the module, the students know solution approaches to process information with THz carriers and/or THz bandwidths and to transmit it via wireless channels and optical fibres. At the same time, the students can design the required THz systems for signal transmission with THz carriers and/or THz bandwidths and spectroscopy.
2	**Contents of the module** - Components for the generation and detection of THz waves - THz spectroscopy - Interaction of THz radiation with matter - Material investigation with THz waves - THz communication - Wireless THz transmission systems - Transmission of optical signals with THz bandwidth - Processing of very large bandwidth signals
3	**Forms of teaching and courses** Lecture "THz-Systemtechnik / THz-Photonik", 3 SWS Exercise "THz-Systemtechnik / THz-Photonik", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: written examination 90 minutes or oral examination 30 minutes
6	**Literature** . R. A. Lewis, Terahertz Physics, Cambridge University Press, ISBN 978-1-107-01857-0
7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute for High Frequency Technology, TUBS
9	**Person responsible for the module** Prof. Dr Thomas Schneider

Electromagnetic theory for high frequency technology		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 6	**Frequency of the offer** WiSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:180 h	Of which attendance time: 56 h	Thereof self-study: 124 h
Further use of the module TUBS		

1	**Qualification goals** After completing the module, the students have a deeper understanding and a well-founded view of the theory of electromagnetic waves with regard to the solution of the homogeneous wave equation (waveguide structures) and the solution of the inhomogeneous wave equation (antennas). They have become familiar with various analytical and numerical solution methods for electromagnetic problems and have implemented them exemplarily themselves as well as applied them within the framework of commercial 3D-EM software. They can select problem-adapted solution methods and apply them to electromagnetic problems in a well-founded manner. In accordance with the didactic concept of the course and the design of the individual components, interdisciplinary qualifications are taught and practised. In the context of papers, colloquia and final presentations, these are scientific writing and documentation, conversation and presentation techniques as well as teamwork in the laboratory or project.
2	**Contents of the module** - Theory of time-harmonic electromagnetic fields (Maxwell's equations, wave equations, energy theorem, uniqueness theorem, reciprocity) - Calculation methods (vector potentials, Lorenz calibration, solution of the (in)homogeneous wave equation, source integrals, Green's function) - Natural waves of waveguides, surface waves, leakage waves - Radiation fields (Huygens principle, image theory, Fresnel and Fraunhofer approximation) - Introduction to the numerical calculation of electromagnetic problems: (FDTD, method of moments, eigenwave evolution) - Exemplary implementation of solution methods in Matlab or Python - Calculation of electromagnetic structures with commercial 3D-EM software
3	**Forms of teaching and courses** Lecture "Electromagnetic Theory for High Frequency Technology", 2 SWS Exercise "Electromagnetic Theory for High Frequency Technology", 2 SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: Written examination 90 minutes or oral examination 30 minutes or term paper or VbP (semester project)

6	**Literature** . Harrington, Time-harmonic Electromagnetic Fields, Wiley & Sons, ISBN 047120806X . Unger, Electromagnetic Theory for High Frequency Technology I + II, Hüthig, ISBN 377851573X, ISBN 3778515748 . Pozar, Microwave Engineering, Wiley & Sons, ASIN B001QA4I9C
7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute for High Frequency Technology, TUBS
9	**Person responsible for the module** Prof. Dr.-Ing. Jörg Schöbel

Information theory		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** WiSe	**Language** English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:150 h	Of which attendance time: 42 h	Thereof self-study: 108 h
Further use of the module TUBS		

1	**Qualification goals** In the module, an introduction to the basics of Shannon's information theory is given. The aim is for the students to be able to derive essential information-theoretical results for the maximum possible lossless (source coding) and lossy (rate-distortion theory) compression of data and for the maximum speed of a reliable data transmission (channel coding). The tools required for the analytical considerations in the form of information measures (entropy, transinformation, capacity, etc.) as well as their properties (typical sequences) are dealt with as well as simple codes that can be used in practice (block codes and turbo codes and polar codes).
2	**Contents of the module** Basic concepts from probability theory - Event, probability, random variable, random vector, random process, convergence of random sequences, convergence theorems Basic concepts from information theory - Measures for discrete random variables: Entropy, conditional entropy, relative entropy, transinformation, conditional transinformation, inequalities. - Measures for continuous random variables: Differential entropy, conditional differential entropy, relative entropy, transinformation, conditional TI, inequalities. - Measures for random sequences - Typical sequences and asymptotic uniform distribution property Sources and source coding - Definition and properties - Source coding for discrete memoryless sources (fixed and variable length) - Selected source codes: Morse, Huffman, Shannon-Fano-Elias Data transmission and channel capacity - Discrete memoryless channel: Channel coding theorem - Discrete memoryless channel with state: channel capacities - Gaussian channel: Model and channel coding theorem - Band-limited Gaussian channel, vector-valued Gaussian channels
3	**Forms of teaching and courses** Lecture "Information Theory", 2 SWS Exercise "Information Theory", 2 SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**

	Study achievements: -
	Examination achievements: Written exam 90 min or oral exam 30 min
6	**Literature** - R.W. Yeung: Information Theory and Network Coding, Part I, Springer, 2008. - R.W. Yeung: A First Course in Information Theory, Springer, 2002. - T.M. Cover and J.A. Thomas: Elements of Information Theory, Wiley-Interscience, 2006. - R.G. Gallager: Information Theory and Reliable Communication, Wiley, 1968. - R.G. Gallager: Principles of Digital Communication, Cambridge University Press, 2008. - S. Moser: S. Moser: Information Theory, https://moser-isi.ethz.ch/scripts.html#it
7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute for Communications Engineering, TUBS
9	**Person responsible for the module** Prof. Dr.-Ing. Eduard Jorswieck

Antennas and radiation fields		Identification number/test code
Master Quantum Engineering		**Module type** Elective
Credit points 6	**Frequency of the offer** SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:180 h	Of which attendance time: 56 h	Thereof self-study: 124 h
Further use of the module TUBS		

1	**Qualification goals** After completing the module, the students have a deeper understanding of the electromagnetic theory for radiation fields as well as a basic understanding of wave propagation and related phenomena (e.g. radar cross-section). They have become familiar with different types of antenna elements as well as array antennas and have a clear and well-founded theoretical understanding of their electromagnetic properties and their characteristics. The students have gained initial experience in using modern 3D EM simulation tools and modern RF measurement technology and are able to acquire further in-depth knowledge in the application of these tools themselves.
2	**Contents of the module** - Maxwell's theory and calculation methods (wave equations, solution of the inhomogeneous wave equation, Source integrals, Huygens principle, image theory, Hertzian dipole) - Simple antenna shapes, antenna characteristics - Array antennas and beamforming, synthesis of antenna patterns - Aperture antennas, Fourier transform, horn and slot radiators, parabolic antennas, physical optics - Wave propagation, diffraction limits of free propagation, static models, radar cross section - Antenna and RCS measurement technology - State-of-the-art technology and current research
3	**Forms of teaching and courses** Lecture "Antennas and Radiation Fields", 2 SWS Exercise "Antennas and Radiation Fields", 2 SWS
4a	**Participation requirements** ---
4b	**Recommendations** Mathematics, Electromagnetic Fields, Fundamentals of Information Technology, Conduction Theory
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: Written examination 90 minutes or oral examination 30 minutes or term paper
6	**Literature** . Unger, High Frequency Technology in Radio and Radar, Teubner-Verlag, ISBN 3519300184

	. Unger, Elektromagnetische Theorie für die - Hochfrequenztechnik, Hüthig-Verlag, ISBN 377851573X . Pozar, Microwave Engineering, Wiley, ASIN B001QA4I9C
7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute for High Frequency Technology, TUBS
9	**Person responsible for the module** Prof. Dr.-Ing. Jörg Schöbel

Linear microwave circuits with practical course		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 6	**Frequency of the offer** WiSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:180 h	Of which attendance time: 56 h	Thereof self-study: 124 h
Further use of the module TUBS		

1	**Qualification goals** After completing the module, students have an in-depth understanding of passive and active linear microwave circuits, especially filters and amplifiers. They are able to design linear microwave circuits and have used corresponding design procedures on a practical example.
2	**Contents of the module** - Matching structures, binomial and Chebyshev transformers, Bode-Fano criterion - pin diode, microwave switch and phase shifter - Bipolar transistor, HBT, FET, HEMT, amplifier, LNA, power amplifier - Design and realisation of microwave filters - Design of linear microwave circuits with commercial design software
3	**Forms of teaching and courses** Lecture "Linear Microwave Circuits", 2 SWS Exercise "Linear Microwave Circuits", 1 SWS Practical course
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: Written examination 90 minutes or oral examination 30 minutes or term paper or VbP (semester project)
6	**Literature** . Pozar, Microwave Engineering, Wiley, ASIN B001QA4I9C . Unger, Harth, High Frequency Semiconductor Electronics, Hirzel, ISBN 3777602353
7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute for High Frequency Technology, TUBS
9	**Person responsible for the module** Prof. Dr.-Ing. Jörg Schöbel

Digital measurement data processing with microcomputers with practice		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 6	**Frequency of the offer** SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:180 h	Of which attendance time: 70 h	Thereof self-study: 110 h
Further use of the module TUBS		

1	**Qualification goals** After completing the module "Digital measurement data processing with microcomputers", the students have an overview of the functioning and programming of microcontrollers for measurement data processing. The acquired practical knowledge enables the programming of embedded systems for metrological applications. In accordance with the didactic concept of the course and the design of the individual components, interdisciplinary qualifications are taught and practised. In the context of papers, colloquia and final presentations, these are scientific writing and documentation, conversation and presentation techniques as well as teamwork in the laboratory or project.
2	**Contents of the module** - Statistical treatment of measurement data, - Interpolation of measurement data, - Signal analysis: discrete (DFT) and fast (FFT) Fourier transformation - z-transformation: digital filters, correlation, simulation of a closed control loop, - Controller and controlled system as IIR and FIR filters. - Assembly language of microprocessors - Implementation of the algorithms of digital signal processing in assembler and C
3	**Forms of teaching and courses** Lecture "Digital Measurement Data Processing with Microcomputers", 2 SWS Exercise "Digital Measurement Data Processing with Microcomputers", 1 SWS Practical part, 2SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: Oral exam 30 min (written exam 120 min only with very large numbers of participants)
6	**Literature** . Weber, H.: Laplace Transformation, Teubner Verlag, Stuttgart, 1984, ISBN 978-3519001416 . Doetsch, G.: Anleitung zum praktischen Gebrauch der Laplace-Transformation und der z-Transformation, Oldenbourg Verlag, München,

	Wien, 1985, ISBN 978-3486298451 . Stearns, S.D.: Digitale Verarbeitung analoger Signale, Oldenbourg Verlag, Munich, Vienna, 1979, ISBN 978- 3486245288 . Birk, H.; Swik, R.: Mikroprozessoren und Mikrorechner und ihre Anwendung in der Automatisierungstechnik, Oldenbourg Verlag, München, Wien, 1983, ISBN 978-3486244328
7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute of Electrical Measurement and Fundamentals of Electrical Engineering, TUBS
9	**Person responsible for the module** Prof.Dr.rer.nat. Meinhard Schilling

Digital circuits		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:150 h	Of which attendance time: 42 h	Thereof self-study: 108 h
Further use of the module TUBS		

1	**Qualification goals** After completing the module, students have a basic understanding of digital circuit technology from chip to system. The students are able to analyse and modify the functioning of both basic digital circuits and complex composite circuit structures. In doing so, they can also take into account realistic effects such as runtimes and interference.
2	**Contents of the module** - Basic concepts - Pulse technology (incl. lines, faults) - Digital circuit families (CMOS, ECL, ...) - Digital flip-flop circuits, time elements and oscillators - Stability and synchronisation of flip-flops - Composite circuit structures (PLA, ROM, RAM, FPGA)
3	**Forms of teaching and courses** Lecture "Digital Circuits", 2 SWS Exercise "Digital Circuits", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: Written exam 150 minutes or oral exam 30 minutes
6	**Literature** . R. Ernst and I. Könenkamp: Digital Circuit Technology for Electrical Engineers and Computer Scientists, 1995 . Tom Granberg: Digital Techiques for High Speed Design, Pearson Education, 2004, ISBN 0-13-142291-x
7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute for Data Technology and Communication Networks, TUBS
9	**Person responsible for the module** Prof. Dr.-Ing. Harald Michalik

Fundamentals of Digital Signal Processing		**Identification number/test code**
Master Quantum Engineering		**Module type** Elective
Credit points 5	**Frequency of the offer** SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 1 or Semester 2	**Module duration** 1 semester
Student workload Total:150 h	Of which attendance time: 42 h	Thereof self-study: 108 h
Further use of the module TUBS		

1	**Qualification goals** After completing this module, students will have basic knowledge on the tools of digital signal processing in the time and frequency domain and can apply these tools to corresponding problems.
2	**Contents of the module** - Discrete-time signals and systems - Fourier transforms - Z-transforms and applications - Discrete-time IIR filter design - Discrete-time FIR filter design - Discrete Fourier Transform (DFT) and Fast Fourier Transform (FFT) - Basics of multi-rate processing and filter banks
3	**Forms of teaching and courses** Lecture "Fundamentals of Digital Signal Processing", 2 SWS Exercise "Fundamentals of Digital Signal Processing", 1 SWS
4a	**Participation requirements** ---
4b	**Recommendations** ---
5	**Requirements for the award of credit points**
	Study achievements: -
	Examination achievements: written exam, 120 minutes or oral examination 30 minutes
6	**Literature** . A.V. Oppenheim, R.W. Schafer, J.R. Buck: "Discrete-Time Signal Processing" , Pearson Verlag, 2004 . K.D. Kammeyer, K. Kroschel: "Digitale Signalverarbeitung" , Teubner Verlag, 2002 . A.V. Oppenheim, R.W. Schafer, J.R. Buck: "`Discrete Time Signal Processing" , Prentice-Hall, 2004 . H.-W. Schüßler: "Digitale Signalverarbeitung 1" , Springer Verlag, 1994
7	**Further information** TUBS course, as required Hybrid
8	**Organisational unit** Institute for Communications Engineering, TUBS
9	**Person responsible for the module** Prof. Dr.-Ing. Tim Fingscheidt

Master's thesis and research phase

<table>
<tr><td colspan="3">**Research internship / project planning**</td><td>**Identification number/test code**</td></tr>
<tr><td colspan="3">**Master Quantum Engineering**</td><td>**Module type**
Mandatory</td></tr>
<tr><td colspan="2">**Credit points**
30 LP</td><td>**Frequency of the offer**
WiSe/SoSe</td><td>**Language**
German / English</td></tr>
<tr><td colspan="2">**Area of competence**
---</td><td>**Recommended semester**
3rd semester</td><td>**Module duration**
1 semester</td></tr>
<tr><td colspan="4">**Student workload**</td></tr>
<tr><td colspan="2">Total: 900 h</td><td>Of which attendance time: -</td><td>Of which self-study: 900 h</td></tr>
<tr><td colspan="4">**Further use of the module**
M. Sc. Physics, M. Sc. Meteorology</td></tr>
<tr><td>1</td><td colspan="3">**Qualification goals**
Students are able to familiarise themselves with the measurement methods or theoretical concepts of a research area. They are able to get an overview of the specialised literature on a research project. The students are able to work in an (internationally composed) team and to communicate in German and English without any problems. The students have acquired social skills that enable them to integrate into a research or development team. They can work independently in a scientific manner and plan complex projects. The students can research independently and get an overview of the partly English-language specialist literature on a research project. They are able to give a scientific presentation and present their own research project in the context of the current state of science.</td></tr>
<tr><td>2</td><td colspan="3">**Contents of the module**
- Literature research
- Familiarisation with theoretical procedures and experimental procedures respectively
- Discussion of problems of current research in the working group seminar
- Definition of a scientific problem
- Project management methods
- Preparation, presentation and discussion of a project plan</td></tr>
<tr><td>3</td><td colspan="3">**Forms of teaching and courses**
Internship "Research Internship"
Project "Project Planning for the Master's Thesis"
Seminar "Working Group Seminar"</td></tr>
<tr><td>4a</td><td colspan="3">**Participation requirements**
---</td></tr>
<tr><td>4b</td><td colspan="3">**Recommendations**
Advanced specialisation modules of the respective Master's degree programme</td></tr>
<tr><td rowspan="3">5</td><td colspan="3">**Requirements for the award of credit points**</td></tr>
<tr><td colspan="3">*Study achievements*:
Seminar performance</td></tr>
<tr><td colspan="3">*Examination achievements*: -</td></tr>
<tr><td>6</td><td colspan="3">**Literature**
. Current literature on the respective research area
. Alley, The Craft of Scientific Presentation, Springer
. Stickel-Wolf, Wolf, Wissenschaftliches Arbeiten und Lerntechniken, ISBN: 3-</td></tr>
</table>

	409-31826-7, Gabler Verlag . Steinle, Bruch, Lawa, (eds.), Project Management: Instrument of Modern Service, 1995, ISBN 3- 929368-27-7, FAZ . Little, (ed.), Management der Hochleistungsorganisation, Gabler Verlag, Wiesbaden, 1990
7	**Further information** ---
8	**Organisational unit** Versch. Faculties
9	**Person responsible for the module** Dean of Studies

Master thesis		**Identification number/test code**
Master Quantum Engineering		**Module type** Mandatory
Credit points 30	**Frequency of the offer** WiSe/SoSe	**Language** German / English
Area of competence ---	**Recommended semester** Semester 4	**Module duration** 1 semester
Student workload Total: 900 h	Of which attendance time: -	Of which self-study: 900 h
Further use of the module M. Sc. Physics, M. Sc. Meteorology		

1	**Qualification goals** The students are able to work independently on a research project. They are able to structure, prepare and carry out scientific projects under guidance. They gain an overview of the current literature and analyse and solve complex problems. The students can lead critical discussions about their own and others' research results and deal constructively with questions and criticism. The students are proficient in German and English technical language. They are able to give a scientific lecture and present their own results in the context of the current state of science.
2	**Contents of the module** - Independent work on a current scientific problem in an international research environment - Written documentation and oral presentation of the research project and the results - Scientific discussion of the results
3	**Forms of teaching and courses** ---
4a	**Participation requirements** Research internship/project planning and at least 40 credit points
4b	**Recommendations** ---
5	**Requirements for the award of credit points** *Study achievements: -* *Examination achievements:* Written elaboration of the Master's thesis
6	**Literature** . Current literature on the respective scientific problem . Day, How to write & publish a scientific paper. Cambridge University Press . Walter Krämer, Wie schreibe ich eine Seminar- oder Examensarbeit?, 1999, ISBN: 3-593-36268-6, Group: Study guide, Series: campus concret, Volume: 47.
7	**Further information** ---
8	**Organisational unit** Versch. Faculties
9	**Person responsible for the module** Dean of Studies

be recorded and the candidate as well as the Dean of Studies are to be informed in writing. The first and second examiners are appointed when the topic is issued. The candidate shall be supervised by the first examiner during the preparation of the thesis.