Federal State Autonomous Educational Institution of Higher Education "Moscow Institute of Physics and Technology (National Research University)"

APPROVED
Head of Landau Phystech-School of Physics & Research
A.V. Rogachev

Work program of the course (training module)

course:	Solid-State Quantum Computing/Твердотельные квантовые вычисления
major:	Photonics and Optical Informatics
specialization:	Photonics, Quantum Technologies & 2D Materials/Фотоника, квантовые технологии и двумерные материалы
	Landau Phystech-School of Physics & Research
	Chair of the Russian Quantum Centre
term:	1
qualification:	Master

Semester, form of interim assessment: 1 (fall) - Exam

Academic hours: 30 AH in total, including:
- lectures: 30 AH.
- seminars: 0 AH.
- laboratory practical: 0 AH.

Independent work: 30 AH.

Exam preparation: 30 AH.

In total: 90 AH, credits in total: 2

Author of the program: A.V. Ustinov, doctor of physics and mathematical sciences

The program was discussed at the Chair of the Russian Quantum Centre 30.04.2021

Annotation

This course is primarily devoted to experimental physics - the physical foundations of solid-state quantum computing. Quantum computing is a rapidly developing interdisciplinary field that includes ideas from quantum mechanics, condensed matter physics, quantum optics, and quantum information processing. Over the past few years, quantum computers have gone from a dream to a reality and opened up exciting possibilities for the future. While classical computers encode information in bits, quantum computers are built using quantum bits or qubits. The lecture course will cover various types of qubits - quantum "hardware" that can be used or is already being used to create quantum computers based on solid-state technologies.

We will start with a brief introduction to the concept of quantum information processing. Various experimental implementations of qubits will then be discussed. After a brief overview of microscopic qubits (atoms, ions, photons), we will talk about existing solid-state quantum platforms, such as semiconductor quantum dots, diamond vacancies, solid-state impurity spins, and other quantum two-level systems. These approaches currently allow you to create the simplest one- or two-qubit schemes. We will also briefly discuss interesting theoretical proposals for as yet unexplored types of qubits, using, for example, electrons on the surface of superfluid helium, impurity spins in fullerenes, and others.

The course will focus on superconductors. After a brief introduction to superconductivity, we will discuss superconducting quantum circuits in detail. Such multi-qubit schemes are currently used in existing quantum computers implemented by Google, IBM, Rigetti, and other IT companies. We will discuss the functioning of various types of superconducting qubits, the sources of losses and the causes of energy dephasing, various decoherence mechanisms, and strategies for increasing the coherence of superconducting qubits. During the last few lectures, we will focus on advanced topics such as quantum electrodynamics of circuits, manipulation and reading of qubits, and also talk about error correction methods of quantum computing.

1. Study objective

Purpose of the course

To introduce students to one of the main directions of the development of quantum technologies – quantum computing, in particular, solid-state quantum computing.

Tasks of the course

teach students to navigate the basic physical platforms and algorithms for processing and transmitting quantum information.

2. List of the planned results of the course (training module), correlated with the planned results of the mastering the educational program

Mastering the discipline is aimed at the formation of the following competencies:

Code and the name of the competence	Competency indicators
Gen.Pro.C-1 Gain fundamental scientific knowledge in the field of physical and mathematical sciences	Gen.Pro.C-1.1 Apply fundamental scientific knowledge in the field of physical and mathematical sciences
Gen.Pro.C-2 Acquire an understanding of current scientific and technological challenges in professional settings, and scientifically formulate professional objectives	Gen.Pro.C-2.3 Understand professional terminology used in modern scientific and technical literature and present scientific results in oral and written form within professional communication
Gen.Pro.C-3 Select and/or develop approaches to professional problem-solving with consideration to the limitations and specifics of different solution methods	Gen.Pro.C-3.1 Analyze problems, plan research strategy to achieve solution(s), propose, and combine solution approaches
	Gen.Pro.C-3.2 Employ research methods to solve new problems, and apply knowledge from various fields of science (technology)
	Gen.Pro.C-3.3 Gain knowledge of analytical and computational methods of problem-solving, understand the limitations for applying the obtained solutions in practice

Gen.Pro.C-4 Successfully perform a task, analyze the results and present conclusions, apply knowledge and skills in the field of physical and mathematical sciences and ICTs	Gen.Pro.C-4.2 Apply knowledge in the field of physical and mathematical sciences to solve problems, make conclusions, and evaluate the obtained results
Pro.C-1 Assign, formalize, and solve tasks, develop and research mathematical models of the studied phenomena and processes, systematically analyze scientific problems and obtain new scientific results	Pro.C-1.1 Locate, analyze, and summarize information on current research findings within a selected subject field
	Pro.C-1.3 Able to apply theoretical and/or experimental research methods in photonics and opto-informatics to a specific scientific problem and interpret the results obtained
Pro.C-3 Professionally use research and testing equipment (devices and installations, specialized software) in a selected subject field	Pro.C-3.1 Understand the operating principles of the equipment and specialized software
	Pro.C-3.2 Conduct an experiment (simulation), using research equipment (software)

3. List of the planned results of the course (training module)

As a result of studying the course the student should:

know:

- the basic concept of quantum information processing;
- experimental implementations of qubits;
- existing solid-state quantum platforms;
- theoretical proposals for as yet unexplored types of qubits, using, for example, electrons on the surface of superfluid helium, impurity spins in fullerenes, and others;
- realizations of superconducting quantum circuits.

be able to:

- solve a broad spectrum of problems related to physical foundations of solid-state quantum computing.

master:

- approaches to create the simplest one- or two-qubit schemes, such as semiconductor quantum dots, diamond vacancies, solid-state impurity spins, and other quantum two-level systems;
- basic principles of functioning of various types of superconducting qubits, decoherence mechanisms, and strategies for increasing the coherence of superconducting qubits.

4. Content of the course (training module), structured by topics (sections), indicating the number of allocated academic hours and types of training sessions

4.1. The sections of the course (training module) and the complexity of the types of training sessions

№	Topic (section) of the course	Types of training sessions, including independent work			
		Lectures	Seminars	Laboratory practical	Independent work
1	Introduction: Basics of quantum computing	2			2
2	Microscopic qubits	2			2
3	Condensed matter qubits	4			4
4	Superconductivity and Josephson junctions	2			2
5	Phase and flux qubits	2			2
6	Charge qubit	2			2
7	Qubit readout and circuit QED	2			2
8	Transmon qubit	2			2
9	Fluxonium, superinductance, g-flux qubit	2			2
10	Qubit manipulation and gates	2			2
11	Decoherence, two-level defects	2			2
12	Qubit readout electronics	2			2

13	Quantum processors, simulators, error correction	4			4
AH in total		30			30
Exam preparation		30 AH.			
Total complexity		90 AH., credits in total 2			

4.2. Content of the course (training module), structured by topics (sections)

Semester: 1 (Fall)

1. Introduction: Basics of quantum computing

A general introduction to quantum computing. Physical limitations of existing classical computing platforms.

2. Microscopic qubits

Microscopic qubits: Atoms, Ions, Photons.

3. Condensed matter qubits

Solid-state qubits: semiconductor quantum dots, impurity spins, NV centers, impurity spins in fullerenes, electrons on the surface of liquid helium. The simplest one-or two-qubit schemes.

4. Superconductivity and Josephson junctions

The main focus of the course will be on superconductors. Therefore, we will devote a separate lecture to the basics of superconductivity and Josephson transitions..

5. Phase and flux qubits

With this lecture, we will begin to discuss superconducting quantum circuits in detail. Such schemes are currently used in existing quantum computers. In this lecture, we will discuss phase and flow qubits.

6. Charge qubit

The first type of superconducting qubit experimentally demonstrated in 1999 was charge qubits. We will discuss these pioneering experiments and talk about the problem of charge noise limiting the coherence time of such qubits.

7. Qubit readout and circuit QED

Quantum electrodynamics of circuits (circuit QED), the Janes-Cummings model, and qubit readout.

8. Transmon qubit

Transmons are currently the most widely used superconducting qubits in quantum processors. We will discuss the advantages of transmons, as well as their limitations and disadvantages.

9. Fluxonium, superinductance, g-flux qubit

The fluxonium is the result of the evolution of the streaming qubit and opens up new perspectives for the construction of quantum circuits. The most important element in such schemes is superinductivity, the properties of which we will discuss.

10. Qubit manipulation and gates

In this lecture, we will talk about manipulating the quantum states of qubits, about one- and two-qubit gates, and about tools for controlling the interaction between qubits.

11. Decoherence, two-level defects

We will talk about the sources of losses and the causes of dephasing of qubits, various decoherence mechanisms, and strategies for increasing the coherence of superconducting qubits.

12. Qubit readout electronics

Manipulating superconducting qubits requires the generation of short microwave pulses with precisely specified amplitude and phase. Qubit measurement involves amplifying weak microwave signals using parametric and low-noise cryogenic amplifiers. We will discuss the details of how practical schemes work.

13. Quantum processors, simulators, error correction

Quantum processors are divided into devices for executing universal quantum protocols and quantum simulators. We will discuss the advantages and practical limitations of different approaches. The second part of the lecture will be devoted to practical methods of error correction in quantum computing.

5. Description of the material and technical facilities that are necessary for the implementation of the educational process of the course (training module)

A classroom equipped with multimedia-projector and projection screen.

6. List of the main and additional literature, that is necessary for the course (training module) mastering

Main literature

1. Введение в физику сверхпроводников [Текст] : учеб. пособие для физ. спец. вузов : доп. М-вом высш. и сред. спец. образования СССР / В. В. Шмидт .— М. : Наука, 1982 .— 237 с. - Библиогр.: с. 230-232. - Предм. указ.: с. 233-235. - 10 500 экз.

1. Риле Ф. Стандарты частоты. Принципы и приложения / Пер. с англ. —М.: ФИЗМАТЛИТ, 2009. - 512 с. - ISBN 978-5-9221-1096-9

Additional literature

1. Quantum Computing: An Applied Approach by Jack D. Hidary, Publisher: Springer
2. Principles and Methods of Quantum Information Technologies, Editors: Yamamoto, Yoshihisa, Semba, Kouichi (Eds.)
3. Quantum Semiconductor Devices and Technologies. Editors: Pearsall, Tom (Ed.)

7. List of web resources that are necessary for the course (training module) mastering

arXiv.org

8. List of information technologies used for implementation of the educational process, including a list of software and information reference systems (if necessary)

Multimedia technologies can be employed during lectures, including presentations.

- Microsoft PowerPoint
- zoom (in case of distance learning)

9. Guidelines for students to master the course

The student studying the discipline must, on the one hand, master the general conceptual apparatus, and on the other hand, must learn to apply theoretical knowledge in practice.

As a result of studying the discipline, the student must know the basic definitions and concepts, be able to apply the acquired knowledge to solve various problems.

Successful completion of the course requires:

- attendance of all classes provided for in the curriculum of the discipline;
- keeping a summary of classes;
- intense independent work of the student.

Independent work includes::

- reading recommended literature;
- study of educational material, preparation of answers to questions intended for self-study;
- solving problems offered to students in the classroom;
- preparation for the performance of intermediate certification tasks.

An indicator of material proficiency is the ability to answer questions on the topics of the discipline without a synopsis.

It is important to achieve an understanding of the material being studied, and not to memorize it mechanically. If it is difficult to study certain topics, questions, you should seek advice from a lecturer.

Intermediate control of students' knowledge is possible in the form of solving problems in accordance with the subject of classes.

SUPPLEMENT

Assessment funds for course (training module)

major:	Photonics and Optical Informatics
specialization:	Photonics, Quantum Technologies & 2D Materials/Фотоника, квантовые технологии и двумерные материалы
	Landau Phystech-School of Physics & Research
	Chair of the Russian Quantum Centre
term:	1
qualification:	Master

Semester, form of interim assessment: 1 (fall) - Exam

Author: A.V. Ustinov, doctor of physics and mathematical sciences

1. Competencies formed during the process of studying the course

Code and the name of the competence	Competency indicators
Gen.Pro.C-1 Gain fundamental scientific knowledge in the field of physical and mathematical sciences	Gen.Pro.C-1.1 Apply fundamental scientific knowledge in the field of physical and mathematical sciences
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Gen.Pro.C-3 Select and/or develop approaches to professional problem-solving with consideration to the limitations and specifics of different solution methods	Gen.Pro.C-3.1 Analyze problems, plan research strategy to achieve solution(s), propose, and combine solution approaches
	Gen.Pro.C-3.2 Employ research methods to solve new problems, and apply knowledge from various fields of science (technology)
	Gen.Pro.C-3.3 Gain knowledge of analytical and computational methods of problem-solving, understand the limitations for applying the obtained solutions in practice
Gen.Pro.C-4 Successfully perform a task, analyze the results and present conclusions, apply knowledge and skills in the field of physical and mathematical sciences and ICTs	Gen.Pro.C-4.2 Apply knowledge in the field of physical and mathematical sciences to solve problems, make conclusions, and evaluate the obtained results
Pro.C-1 Assign, formalize, and solve tasks, develop and research mathematical models of the studied phenomena and processes, systematically analyze scientific problems and obtain new scientific results	Pro.C-1.1 Locate, analyze, and summarize information on current research findings within a selected subject field
	Pro.C-1.3 Able to apply theoretical and/or experimental research methods in photonics and opto-informatics to a specific scientific problem and interpret the results obtained
Pro.C-3 Professionally use research and testing equipment (devices and installations, specialized software) in a selected subject field	Pro.C-3.1 Understand the operating principles of the equipment and specialized software
	Pro.C-3.2 Conduct an experiment (simulation), using research equipment (software)

2. Competency assessment indicators

As a result of studying the course the student should:

know:

- the basic concept of quantum information processing;
- experimental implementations of qubits;
- existing solid-state quantum platforms;
- theoretical proposals for as yet unexplored types of qubits, using, for example, electrons on the surface of superfluid helium, impurity spins in fullerenes, and others;
- realizations of superconducting quantum circuits.

be able to:

- solve a broad spectrum of problems related to physical foundations of solid-state quantum computing.

master:

- approaches to create the simplest one- or two-qubit schemes, such as semiconductor quantum dots, diamond vacancies, solid-state impurity spins, and other quantum two-level systems;
- basic principles of functioning of various types of superconducting qubits, decoherence mechanisms, and strategies for increasing the coherence of superconducting qubits.

3. List of typical control tasks used to evaluate knowledge and skills

Not privided.

4. Evaluation criteria

Checking questions:
1. Physical limitations of existing classical computing platforms.
2. Microscopic qubits: atoms, ions, photons.
3. Solid-state qubits: semiconductor quantum dots, impurity spins, NV centers, impurity spins in fullerenes, electrons on the surface of liquid helium.
4. The simplest one- or two-qubit schemes.
5. Fundamentals of superconductivity and Josephson transitions.
6. Phase and flow qubits
7. The charge qubit. The problem of charge noise.
8. Quantum electrodynamics of circuits (circuit QED), the Janes-Cummings model, and qubit readout.
9. Transmon. Advantages, limitations, and disadvantages.
10. Fluxonium and superinductivity/
11. Manipulation of quantum states of qubits. One- and two-qubit gates.
12. Tools for managing the interaction between qubits.
13. Sources of losses and causes of dephasing of qubits.
14. Decoherence mechanisms and strategies for increasing the coherence of superconducting qubits.
15. Electronics for measuring and controlling qubits. Details of the operation of practical schemes.
16. Quantum processors and simulators. Advantages and practical limitations of different approaches.
17. Correction of errors in quantum computing.

Examples of exam question papers:
Question paper 1.
1. State the Landaur principle and formulate it in the context of quantum information theory. Formulate the fundamental differences between reversible and irreversible calculations.
2. Types of superconducting qubits.
Question paper 2.
1. Describe the main applications of modern quantum technologies and explain their principles. Quantum volume as a characteristic of quantum computers.
2. Formulate the DiVincenzo criteria. Give a universal set of quantum gates.
Question paper 3.
1. Formulate the Church-Turing-Deutsch principle. Present the concept of quantum computing.
2. What is a streaming qubit? How does it differ from fluxonium?

Assessment “excellent (10)” is given to a student who has displayed comprehensive, systematic and deep knowledge of the educational program material, has independently performed all the tasks stipulated by the program, has deeply studied the basic and additional literature recommended by the program, has been actively working in the classroom, and understands the basic scientific concepts on studied discipline, who showed creativity and scientific approach in understanding and presenting educational program material, whose answer is characterized by using rich and adequate terms, and by the consistent and logical presentation of the material;

Assessment “excellent (9)” is given to a student who has displayed comprehensive, systematic knowledge of the educational program material, has independently performed all the tasks provided by the program, has deeply mastered the basic literature and is familiar with the additional literature recommended by the program, has been actively working in the classroom, has shown the systematic nature of knowledge on discipline sufficient for further study, as well as the ability to amplify it on one’s own, whose answer is distinguished by the accuracy of the terms used, and the presentation of the material in it is consistent and logical;

Assessment “excellent (8)” is given to a student who has displayed complete knowledge of the educational program material, does not allow significant inaccuracies in his answer, has independently performed all the tasks stipulated by the program, studied the basic literature recommended by the program, worked actively in the classroom, showed systematic character of his knowledge of the discipline, which is sufficient for further study, as well as the ability to amplify it on his own;

Assessment “good (7)” is given to a student who has displayed a sufficiently complete knowledge of the educational program material, does not allow significant inaccuracies in the answer, has independently performed all the tasks provided by the program, studied the basic literature recommended by the program, worked actively in the classroom, showed systematic character of his knowledge of the discipline, which is sufficient for further study, as well as the ability to amplify it on his own;

Assessment “good (6)” is given to a student who has displayed a sufficiently complete knowledge of the educational program material, does not allow significant inaccuracies in his answer, has independently carried out the main tasks stipulated by the program, studied the basic literature recommended by the program, showed systematic character of his knowledge of the discipline, which is sufficient for further study;

Assessment “good (5)” is given to a student who has displayed knowledge of the basic educational program material in the amount necessary for further study and future work in the profession, who while not being sufficiently active in the classroom, has nevertheless independently carried out the main tasks stipulated by the program, mastered the basic literature recommended by the program, made some errors in their implementation and in his answer during the test, but has the necessary knowledge for correcting these errors by himself;

Assessment “satisfactory (4)” is given to a student who has discovered knowledge of the basic educational program material in the amount necessary for further study and future work in the profession, who while not being sufficiently active in the classroom, has nevertheless independently carried out the main tasks stipulated by the program, learned the main literature but allowed some errors in their implementation and in his answer during the test, but has the necessary knowledge for correcting these errors under the guidance of a teacher;

Assessment “satisfactory (3)” is given to a student who has displayed knowledge of the basic educational program material in the amount necessary for further study and future work in the profession, not showed activity in the classroom, independently fulfilled the main tasks envisaged by the program, but allowed errors in their implementation and in the answer during the test, but possessing necessary knowledge for elimination under the guidance of the teacher of the most essential errors;

Assessment “unsatisfactory (2)” is given to a student who showed gaps in knowledge or lack of knowledge on a significant part of the basic educational program material, who has not performed independently the main tasks demanded by the program, made fundamental errors in the fulfillment of the tasks stipulated by the program, who is not able to continue his studies or start professional activities without additional training in the discipline in question;

Assessment “unsatisfactory (1)” is given to a student when there is no answer (refusal to answer), or when the submitted answer does not correspond at all to the essence of the questions contained in the task.

5. Methodological materials defining the procedures for the assessment of knowledge, skills, abilities and/or experience

The course is graded at an oral exam. The questionning starts with a random task assigned to each student and time given for completion of the task. No aids are allowed. The student then proceeds to a chat with the examiner, at which he/she presents his/her solution to the assigned task. The examiner then asks the student several questions that evenly cover the course content. A final grade is assigned based on the quality of answers and demonstrated level of understanding.