

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

APPROVED

**и.о. директора физтех-школы
физики и исследований им.
Ландау**

A.A. Voronov

Work program of the course (training module)

course:	Labs in Quantum Photonics and Cryptography/Лабораторный практикум по квантовой фотонике и криптографии
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: 2 (spring) - Grading test

Academic hours: 30 АН in total, including:

lectures: 0 АН.

seminars: 0 АН.

laboratory practical: 30 АН.

Independent work: 60 АН.

In total: 90 АН, credits in total: 2

Author of the program: V.V. Makarov, phd (candidate of physics and mathematical sciences)

The program was discussed at the Chair of the Russian Quantum Centre 02.03.2020

Annotation

The labs give the student an outlook on modern devices and technological solutions in quantum photonics and cryptography. By accomplishing six practical works, the student gets acquainted with single-photon detectors and methods of their characterization, fiber-optics interferometers and reflectometry, learns to work with a quantum key transmission system and a hardware random number generator. State-of-the-art signal generators, electronic counters, oscilloscopes and time recording systems, as well as semiconductor lasers, photodetectors and optical signal modulators, and computer control systems are used in the labs.

1. Study objective

Purpose of the course

To familiarize students with state-of-the-art laboratory instrumentation and standard operating procedures in quantum photonics and cryptography.

Tasks of the course

- To develop practical skills of use of modern tools and device of quantum data processing based on photonics;
- to reinforce the theoretical knowledge acquired on preceeding lectures.

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
UC-1 Use a systematic approach to critically analyze a problem and develop an action plan	UC-1.1 Systematically analyze the problem situation, identify its components and the relations between them
	UC-1.2 Search for solutions by using available sources
	UC-1.3 Develop a step-by-step strategy for achieving a goal, foresee the result of each step, evaluate the overall impact on the planned activity and its participants
UC-2 Manage all stages of a research project	UC-2.2 Forecast the project outcomes, plan necessary steps to achieve the outcomes, chart the project schedule and monitoring plan
	UC-2.4 Publicly present the project results (or results of its stages) via reports, articles, presentations at scientific conferences, seminars, and similar events
UC-3 Organize and manage a team and develop the team strategy to achieve the objectives	UC-3.1 Organize and coordinate the work of the project stakeholders and help resolve disputes and conflicts
	UC-3.4 Plan teamwork, distribute tasks to team members, hold discussions of different ideas and opinions
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-1.2 Able to summarise and critically evaluate experiences and research results in the field of photonics and opto-informatics
	Gen.Pro.C-1.3 Understands the interdisciplinary links in mathematics and physics and is able to apply them to problems in photonics and opto-informatics
Gen.Pro.C-2 Acquire an understanding of current scientific and technological challenges in professional settings, and scientifically formulate professional objectives	Gen.Pro.C-2.1 Has an understanding of the current state of research in photonics and opto-informatics
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-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
	Gen.Pro.C-4.3 Justify the chosen method of scientific research
Gen.Pro.C-5 Undertake professional training, achieve professional growth, and become a team leader in a professional sphere, tolerant of social, ethnic, religious and cultural differences	Gen.Pro.C-5.1 Tolerate social, ethnic, religious, and cultural differences in teamwork
	Gen.Pro.C-5.2 Manage a small professional team
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-1.3 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-2 Organize and conduct scientific research and testing independently or as a member (leader) of a small research team	Pro.C-2.1 Able to plan and carry out research in photonics and opto-informatics independently or as part of a research team
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)
	Pro.C-3.3 Evaluate the accuracy of the experimental (numerical) results

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

As a result of studying the course the student should:

know:

Practical aspects of operating with photon emitters and detectors, fiber-optic interferometers, state-of-the-art instrumentation and computer system of the photonic lab.

be able to:

- Use modern instruments and data processing systems of the photonic lab;
- apply theoretical knowledge on quantum data processing to handle practical task.

master:

Basic skills to work in a photonic lab.

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	Lab #1. Single-photon detector.			5	10
2	Lab #2. Single-photon interferometry with fiber optics.			5	10
3	Lab #3. Single-photon reflectometry and plug-and-play interferometer scheme.			5	10
4	Lab #4. Fiber-optic quantum key distribution system.			5	10
5	Lab #5. Quantum-optical random number generator.			5	10
6	Lab #6. Bright-light control of a single-photon detector.			5	10

AH in total			30	60
Exam preparation	0 AH.			
Total complexity	90 AH., credits in total 2			

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

Semester: 2 (Spring)

1. Lab #1. Single-photon detector.

Measurements of basic characteristics of a single-photon avalanche diode: quantum efficiency, linearity and maximum count speed, dead time of detection, post-pulses, and jitter.

2. Lab #2. Single-photon interferometry with fiber optics.

Obtaining light interference in a fiber-optic interferometer. Stabilization of the interferometer. Young's experiment (interference pattern from single photons).

3. Lab #3. Single-photon reflectometry and plug-and-play interferometer scheme.

An optical time-domain reflectometer (OTDR) for fiber-optic communication systems. Identification of components and measurement of their characteristics using a reflectogram. Switching to photon counting mode to increase sensitivity.

4. Lab #4. Fiber-optic quantum key distribution system.

Setting up and running a quantum key distribution system using autocompensation fiber-optic circuit. Testing its main characteristics.

5. Lab #5. Quantum-optical random number generator.

Setup and run of a hardware random number generator based on the phase of spontaneous emission of a semiconductor laser diode. Checking the correctness of its operation mode, reception and statistical testing of the resulting output sequence.

6. Lab #6. Bright-light control of a single-photon detector.

Demonstration of the blinding of a single-photon avalanche diode and of its classical control using bright light. Measurement of characteristics of single-photon avalanche diode under attack on the quantum key transfer system. Testing of a possible solution.

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

Laboratory facilities of laboratory of quantum communications and laboratory of quantum hacking of RQC maintained by the staff of labs and of "QRate" company.

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

Main literature

1. Введение в квантовую теорию информации [Текст] : [лекции для студентов вузов] / А. С. Холево ; Независимый Моск. ун-т ; Высший колледж математ. физики .— М : МЦНМО, 2002 .— 128 с.

Additional literature

1. Оптика и фотоника. Принципы и применения. В 2 т. Т. 2 /Б. Салех, М. Тейх ; пер. с англ. В. Л. Дербова%*d*Fundamentals of Photonics. Долгопрудный, Интеллект, 2012
2. Оптика и фотоника. Принципы и применения. В 2 т. Т. 1 /Б. Салех, М. Тейх ; пер. с англ. В. Л. Дербова%*d*Fundamentals of Photonics. Долгопрудный, Интеллект, 2012

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

1. Guide materials to each lab: <http://www.vad1.com/c/qphcl/>
2. <https://arxiv.org/> - open-access archive for articles in the fields of physics, mathematics, computer science, etc.

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

Laboratory facilities are connected to computers with specialized software for data acquisition and processing.

9. Guidelines for students to master the course

For the successful assimilation of the course, in addition to attending labs, students are required to perform homework whose amount in hours should be not less than the number of hours specified in the curricula of the faculties. Studying at home includes:

- reading the guide materials prior to the lab in order to be able to answer questions from the teacher based on the guide materials;
- processing and critical analysis of the results of the lab, and performing written report, normally one week after the lab;
- reading additional literature, including reviews in articles, on physical phenomena under study and state-of-the-art experimental techniques as well as their practical applications.

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: 2 (spring) - Grading test
Author: V.V. Makarov, phd (candidate of physics and mathematical sciences)

1. Competencies formed during the process of studying the course

Code and the name of the competence	Competency indicators
UC-1 Use a systematic approach to critically analyze a problem and develop an action plan	UC-1.1 Systematically analyze the problem situation, identify its components and the relations between them
	UC-1.2 Search for solutions by using available sources
	UC-1.3 Develop a step-by-step strategy for achieving a goal, foresee the result of each step, evaluate the overall impact on the planned activity and its participants
UC-2 Manage all stages of a research project	UC-2.2 Forecast the project outcomes, plan necessary steps to achieve the outcomes, chart the project schedule and monitoring plan
	UC-2.4 Publicly present the project results (or results of its stages) via reports, articles, presentations at scientific conferences, seminars, and similar events
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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-1.3 Understands the interdisciplinary links in mathematics and physics and is able to apply them to problems in photonics and opto-informatics
Gen.Pro.C-2 Acquire an understanding of current scientific and technological challenges in professional settings, and scientifically formulate professional objectives	Gen.Pro.C-2.1 Has an understanding of the current state of research in photonics and opto-informatics
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)
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Pro.C-2 Organize and conduct scientific research and testing independently or as a member (leader) of a small research team	Pro.C-2.1 Able to plan and carry out research in photonics and opto-informatics independently or as part of a research team
Pro.C-3 Professionally use research and testing	Pro.C-3.1 Understand the operating principles of the equipment and specialized software

Pro.C-3 Professionally use research and testing equipment (devices and installations, specialized software) in a selected subject field

Pro.C-3.2 Conduct an experiment (simulation), using research equipment (software)

Pro.C-3.3 Evaluate the accuracy of the experimental (numerical) results

2. Competency assessment indicators

As a result of studying the course the student should:

know:

Practical aspects of operating with photon emitters and detectors, fiber-optic interferometers, state-of-the-art instrumentation and computer system of the photonic lab.

be able to:

- Use modern instruments and data processing systems of the photonic lab;
- apply theoretical knowledge on quantum data processing to handle practical task.

master:

Basic skills to work in a photonic lab.

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

Examples of questions before the start of the lab:

1. Give the main goals of the lab and how they can be achieved.
2. Draw the experimental setup.
3. Explain the operating principles of the devices used in the lab.

Typical tasks during the discussion of the report:

1. Give the explanation of characteristic features of data obtained and experimental technique.
2. Analyse the results and explain the conclusions.
3. Revise the report, make additional measurements.

Prior to the lab each student should read guide materials and must satisfactorily answer questions from the teacher based on the guide materials, in order to be allowed to start the lab. Students work on each lab in pairs and deliver one written report, normally one week after the lab. (In case of odd number of students in the class, some labs may be done by a single student.) The teacher reads the report and either accepts it or discusses issues with the pair, which may lead to a revision of the report and/or repeating some measurements. If the pair has more than one outstanding report, they are not admitted to further labs.

4. Evaluation criteria

1. Basic characteristics of a single-photon avalanche diode.
2. Obtaining light interference in a fiber-optic interferometer. Stabilization of the interferometer.
3. Young's experiment (interference pattern from single photons).
4. Operation principles of an optical time-domain reflectometer (OTDR) for fiber-optic communication systems. Identification of components and measurement of their characteristics using a reflectogram.
5. Setting up and running a quantum key distribution system using autocompensation fiber-optic circuit. Testing its main characteristics.
6. Hardware random number generator based on the phase of spontaneous emission of a semiconductor laser diode. Checking the correctness of its operation mode, reception and statistical testing of the resulting output sequence.
7. Blinding of a single-photon avalanche diode and its classical control using bright light. Characteristics of single-photon avalanche diode under attack on the quantum key transfer system. Possible solutions.

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 according to the criteria listed above based on acceptance of written reports from all individual labs.