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:	Introduction to Quantum Metrology/Основы квантовой метрологии
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 AH in total, including:
lectures: 30 AH.
seminars: 0 AH.
laboratory practical: 0 AH.

Independent work: 60 AH.

In total: 90 AH, credits in total: 2

Authors of the program:

A.A. Golovizin, candidate of physics and mathematical sciences
V.V. Soshenko, assistant

The program was discussed at the Chair of the Russian Quantum Centre 04.04.2022

Annotation

The course reviews the basic principles and the latest scientific advances in the field of quantum metrology. Quantum metrology is based on the use of quantum states of individual particles or a system as sensors, leading to greater performance (sensitivity, accuracy, etc.) being achieved than attributed to classical measuring instruments.

Prominent examples of quantum sensors are magnetic field sensors based on superconductors, atoms in cells, and NV centers, gyroscopes, optical clocks, and atomic interferometers and gravimeters. The new definition of the International System of Units in terms of fundamental constants is largely motivated by the high precision of various quantum sensors.

1. Study objective

Purpose of the course

Provide students with knowledge of basics of the quantum metrology.

Tasks of the course

Widen the scope of students in the field of quantum mechanics, introduce the physical platforms used for quantum sensors.

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-1.2 Able to summarise and critically evaluate experiences and research results in the field of 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-2.2 Assess the relevance and practical importance of research in professional settings
	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
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-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

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

As a result of studying the course the student should:

know:

the foundations of quantum metrology and magnetometry, the physical platforms on which quantum calculators and sensors are implemented, the implementation of algorithms and measurements with them.

be able to:

explain the basic processes in quantum metrology and in the way quantum sensors work, estimate quantum sensor performance.

master:

the mathematical apparatus of quantum mechanics, especially related to quantum computing and measurement.

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	Physical platforms	4			8
2	Quantum logic operations	2			4
3	Optical clocks	4			8
4	Atomic interferometers, gravimeters	2			4
5	Non-classical states in quantum metrology	2			4
6	Magnetometry	6			12
7	Thermometry in nanoscale	2			4
8	Nuclear magnetic resonance gyroscopy	2			4
9	Electrometry	2			4
10	Methods of sensitivity improvement	4			8
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. Physical platforms

Physical platforms: cold atoms, cold ions, artificial atoms, photons. Main physical platforms on which optical clocks, atomic interferometers and gravimeters are based. Methods for obtaining and preparing particles, n.o. laser cooling, pumping and polarization processes. The advantages and disadvantages of various platforms in a specific application.

2. Quantum logic operations

Basic operations performed on atoms (ions, photons) to prepare and read states. The method of quantum logic, which uses a sparing ion to read the internal state of a "clock" ion.

3. Optical clocks

Principles of operation of optical clocks. Existing clocks on single and ensembles of ions, on neutral atoms in lattices, nuclear transitions. Systematic shifts and errors of optical clocks. Stability and accuracy of optical clocks.

4. Atomic interferometers, gravimeters

The principles of operation of atomic interferometers and gravimeters. Atomic ensembles used for gravimetry. Sensitivity to various external fields and methods of their measurement. The achievable performance of interferometers and gravimeters. Limiting factors.

5. Non-classical states in quantum metrology

Examples of using nonclassical states of light or atomic ensembles to improve the characteristics of quantum sensors. Using squeezed states to overcome the standard quantum noise limit.

6. Magnetometry

Color centers in diamond (nitrogen-vacancy, silicon-vacancy), NV center ground state, spin optical polarization and readout. DC magnetometer operation principles, error estimation for NV-based magnetometer. Superconducting quantum interference device(SQUID). DC-SQUID, RF-SQUID magnetometers. Magnetometer error estimation. Rubidium vapor cell magnetometer.

7. Thermometry in nanoscale

Living cell thermometry via color centers in nanodiamonds. Measurement principle and error estimation.

8. Nuclear magnetic resonance gyroscopy

8. Gyroscope based on Xenon nuclear spin ensemble. Operation principle, continuous induced precession regime. Measurement errors and precision limits.

9. Electrometry

9. Electrometry with Rydberg atoms. Electrometry with color centers in diamond. Measurement errors and precision limits.

10. Methods of sensitivity improvement

Methods of sensitivity improvement. Quantum error correction. Non-demolition measurement.

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.

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

Additional literature

- Dmitry Budker, Derek Kimball Optical Magnetometry/ Cambridge University press, 2013 – 412c. -ISBN 9780511846380
- Ludlow A. D. et al. Optical atomic clocks //Reviews of Modern Physics. – 2015. – T. 87. – №. 2. – C. 637.
- Pezze L. et al. Quantum metrology with nonclassical states of atomic ensembles //Reviews of Modern Physics. – 2018. – T. 90. – №. 3. – C. 035005.

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

- lib.mipt.ru

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

9. Guidelines for students to master the course

Students should learn the basic concepts of quantum communications and cryptography, as well as how to apply their theoretical knowledge in practice.

For the successful assimilation of the course, in addition to attending classes, 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 recomended literature and making notes;
- processing and analysis of lecture materials (using notes, textbooks and scientific articles), answering questions, proving some statements;
- solving problems given on lectures and seminars for self-study;
- preparing for the tests and exams.

SUPPLEMENT

Assessment funds for course (training module)

major:	Photonics and Optical Informatics
specialization:	Photonics, Quantum Technologies & 2D Materials/Фотоника, квантовые технологии и двумерные материалы
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Authors:

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1. Competencies formed during the process of studying the course

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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-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

2. Competency assessment indicators

As a result of studying the course the student should:

know:

the foundations of quantum metrology and magnetometry, the physical platforms on which quantum calculators and sensors are implemented, the implementation of algorithms and measurements with them.

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master:

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

Analyze one of the suggested articles. Examples of article topics:

- Coherent laser spectroscopy of highly charged ions using quantum logic;
- High-sensitivity magnetometry with a single atom in a superposition of two circular Rydberg states;
- Variational Spin-Squeezing Algorithms on Programmable Quantum Sensors;
- A quantum network of clocks.

4. Evaluation criteria

Examples of checking tasks:

1. Calculate the required integration time of the frequency standard signal to achieve a relative systematic error of 1E-18 when interrogating an atomic ensemble with a 800 ms duration Rabi pulse. The measurement period is 1 s, the number of atoms is 10,000, the frequency of the hourly transition is 430 THz.

2. What frequency correction should be made when comparing two optical clocks with an altitude difference of 400 meters.

3. Calculate the difference in gravitational potential at the equator and poles.

4. Calculate shot noise limit of NV-center based DC magnetometer sensitivity for a single NV with coherence time T2*=1us and fluorescence contrast of 30%.

5. How large can be RF-SQUID crossection to have dynamic range of 1uT at least.

Checking questions:

1. Various types of noise, their spectrum and Allan deviation.
2. Characteristics of quantum sensors, sensitivity, stability. Readout methods. Standard quantum limit of measurement.
3. The principle of operation of atomic clocks. Microwave and optical clocks.
4. Main systematic shifts and uncertainty sources of optical clocks.
5. Atomic gravimeters, principles of work. The units used and the characteristic values of the gravitational field from various sources (Moon, equator and poles, etc.). Comparison of classical and atomic gravimeters.
6. Magnetometer on NV center. Calculation of the magnetometer sensitivity in the case of a single NV and an ensemble of color centers
7. Rubidium atomic magnetometer. Magnetometer sensitivity.
8. A gyroscope based on an ensemble of xenon atoms. Induced precession.
9. Josephson effect. SQUID. DC-SQUID magnetometer operation. Sensitivity of SQUID magnetometer.
10. Polarization of the nuclear spin of nitrogen in the NV center in the excited state crossing mode (ESLAC).
11. AC magnetometer based on NV center. Differences from DC magnetometer. Sensitivity estimation.

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 final test. The test 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.