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:	Laser Physics/Физика лазеров
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 Physics and Technology of nanostructures
term:	1
qualification:	Master

Semesters, forms of interim assessment:

1 (fall) - Grading test
2 (spring) - Exam

Academic hours: 60 AH in total, including:
lectures: 30 AH.
seminars: 30 AH.
laboratory practical: 0 AH.

Independent work: 45 AH.

Exam preparation: 30 AH.

In total: 135 AH, credits in total: 3

Authors of the program:

P.B. Ginzburg, doctor of physics and mathematical sciences
D.S. Filonov, phd (candidate of physics and mathematical sciences)

The program was discussed at the Chair of Physics and Technology of nanostructures 01.02.2021

Annotation

The discipline introduces students into the basic concepts of laser operation and laser physics. The audience will be taught basic methods for describing the interaction of light and matter; principles of laser operation; classification of lasers and their modes of action, and fields of application of lasers in modern technology.

1. Study objective

Purpose of the course

to give students knowledge of the basic concepts of laser operation and laser physics.

Tasks of the course

- Acquiring knowledge about methods of light source characterization
- Acquiring knowledge about the basic methods for describing the interaction of light and matter
- Learning how to describe laser action
- Studying the classification of lasers and their modes of action
- Studying applications of lasers in modern technology

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-4 Use modern communication tools in the academic and professional fields, including those in a foreign language	UC-4.3 Present the results of academic and professional activities in various academic events, including international conferences
	UC-4.4 Use modern ICT tools for academic and professional collaboration
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-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
	Gen.Pro.C-4.3 Justify the chosen method of scientific research
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
	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:

1. Methods of describing the basic processes of interaction of light with matter
2. Methods of designing optical resonators
3. Description of laser dynamics via rate equations
4. Characteristics of radiation generated by laser source
5. Applications of laser physics

be able to:

1. Formulate equations of dynamics of lasers
2. Select the correct characteristics of an optical resonator for a particular application
3. Solve a system of coupled equations describing the dynamics of interaction between the active medium and light in the resonator
4. Evaluate the properties, including photon statistics, of radiation generated by a laser

master:

1. Methods of describing laser dynamics
2. Methods of design of laser resonators
3. Methods of describing interaction of light and medium
4. Methods of constructing models of complex physical processes

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	Introductory session: history of lasers and their development	2	2		2
2	Sources of light and their characterization	2	2		2
3	Interaction of light with matter (absorption, spontaneous and stimulated emission)	2	2		2
4	Spectral characteristics of absorption and radiation processes, homogeneous and non-homogeneous line broadening	2	2		2
5	Optical amplifiers, rate equations	3	3		3
6	Laser generation, generation threshold conditions, saturation and other effects	2	2		2
7	Optimal conditions for laser operation	2	2		2
8	Single-mode and multi-mode operating lasers	2	2		4
9	Characterization of laser sources	3	3		6
10	Laser radiation statistics, generation threshold transition	2	2		4
11	Ray optics, ABCD matrix	2	2		4
12	Stability conditions for optical resonators	2	2		4
13	Gaussian beams, stability of optical resonators	2	2		4
14	Summary of material	2	2		4
AH in total		30	30		45

Exam preparation	30 AH.
Total complexity	135 AH., credits in total 3

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

Semester: 1 (Fall)

1. Introductory session: history of lasers and their development

History of the development of light sources. Major milestones in the development of laser technology and its applications. Review of course materials.

2. Sources of light and their characterization

Basic concepts of light source characterization, concept of coherence (spatial and temporal). Methods of coherence measurement. Significance of laser technology in nitrometry problems.

3. Interaction of light with matter (absorption, spontaneous and stimulated emission)

Introduction of basic concepts of absorption and radiation. Black body model. The concept of spontaneous radiation in the Planck model. Einstein's coefficients. Einstein’s rate equations for description of spectrum of black body radiation.

4. Spectral characteristics of absorption and radiation processes, homogeneous and non-homogeneous line broadening

The concept of line width in spontaneous emission processes. Homogeneous and inhomogeneous line broadening. Spectral line broadening in gas and solid-state emitters.

5. Optical amplifiers, rate equations

Formulation of rate equations for three- and four-level systems. Solving equations in continuous and pulsed pumping modes. Formulation of conditions for population inversion.

6. Laser generation, generation threshold conditions, saturation and other effects

Formulation of rate equations for description of radiation in optical resonators. Coupled equations for description of laser generation. Formulation of conditions of laser generation.

7. Optimal conditions for laser operation

Analysis of transient effects in laser generation. Temporal laser modulation. Introduction of optimal laser generation conditions related to the design of the optical resonator. Fabry-Perot resonator analysis.

Semester: 2 (Spring)

8. Single-mode and multi-mode operating lasers

Formulation of laser generation equations assuming one or many modes in the optical resonator. Discussion of homogeneous and inhomogeneous line broadening. Conditions for modal beating.

9. Characterization of laser sources

Continuous and pulsed lasers, Q-switching and modelocking. Analysis of active laser generation media. Overview of semiconductor lasers and nanolasers.

10. Laser radiation statistics, generation threshold transition

Noise of laser sources, Schawlow-Townes line width model. Photon statistics below and above the laser generation threshold.

11. Ray optics, ABCD matrix

Formulation of light propagation in ray optics. ABCD matrix for basic optical elements. Analysis of optical elements using the ABCD matrix.

12. Stability conditions for optical resonators

Stability evaluation of optical resonators using the ABCD matrix. Design of the optical circuits.

13. Gaussian beams, stability of optical resonators

Solution of diffraction problem in the formulation of Gaussian beams. Basic properties of Gaussian beams. Propagation of Gaussian beams in optical circuits in the ABCD matrix formulation. Stability conditions of optical resonators.

14. Summary of material

Review of passed material. Solution of typical problems.

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

1. Lecture classes:
1.1. set of electronic presentations/slides,
1.2. an auditorium equipped with presentation equipment (projector, screen, computer/laptop)
1.3. special technical equipment for disabled students and persons with disabilities.

2. Practical studies:
2.1. seminar-type study room,
2.2. presentation equipment (projector, screen, computer/laptop, laser pointer),
2.3. a lecturer's workplace with a computer with Internet access,
2.4. students' workstations equipped with computers with Internet access designed for work in electronic educational environment,
2.5. general-purpose software packages (text editors, graphic editors),
2.6. special technical means for students with disabilities and persons with disabilities

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

Main literature

1. Принципы лазеров [Текст] : [учеб. пособие для вузов] / О. Звелто ; пер. с англ. Д. Н. Козлова [и др.] ; под науч. ред. Т. А. Шмаонова ; рус. пер. перераб. и доп. при участии автора книги .— 4-е изд. — СПб. : Лань, 2008 .— 720 с.

Literature fund of the basic departament:

- A. Siegman, Lasers; University Science Book: Mill Valley California, 1986

Additional literature

Literature fund of the basic departament:

- R. Loudon. The Quantum Theory of Light; Springer, 2009
- Marlan O. Scully et al, Quantum Optics; Cambridge University Press, 2012

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

- https://lms.mipt.ru/
- https://www.youtube.com/watch?v=pLl3q6WKtxw&list=PLLYQF5WvJdJUIWvYHSG0km9MHf4Vud6yc
- https://www.rp-photonics.com/laser_optics.html

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

When preparing and conducting lectures, the Internet is used.
In addition, Libre Office is used, as well as the Ink Scape graphics package.

9. Guidelines for students to master the course

When studying the discipline "Physics of lasers" students are recommended to attend all lectures and practical classes. During independent work, it is recommended to study all specified sources given in the list of additional literature. Independently listen to courses of auxiliary lectures.

When doing homework, check the intermediate results with the instructor. Answer all theoretical questions given in the section "additional questions" in each homework.

SUPPLEMENT

Assessment funds for course (training module)

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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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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
	Gen.Pro.C-4.3 Justify the chosen method of scientific research
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
	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:

1. Methods of describing the basic processes of interaction of light with matter
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4. Characteristics of radiation generated by laser source
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be able to:

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3. Solve a system of coupled equations describing the dynamics of interaction between the active medium and light in the resonator
4. Evaluate the properties, including photon statistics, of radiation generated by a laser

master:

1. Methods of describing laser dynamics
2. Methods of design of laser resonators
3. Methods of describing interaction of light and medium
4. Methods of constructing models of complex physical processes

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

Not provided.

4. Evaluation criteria

First term - problems for the test:

Each variant of the task contains 1 problem, which is an analytical calculation. Fifteen variants are offered. The conditions of the problems are published in printed form. Problem solutions are presented in printed form.

Control task 1 (Fabry-Perot interferometers and spectral response)
The purpose of this question is to perform a basic analysis of the Fabry-Perot etalon and apply it to several different light sources.

1. The Fabry-Perot etalon is a parallel plate of transparent material with a refractive index of 'n'. The width of the plate is 'd'.

2. A monochromatic plane wave at a given frequency affects the plate at an angle α. Derive the resonance condition (at maximum transmission) relating the geometry of the plate, its refractive index and the frequency of the incident wave. The expressions must be derived from basic principles.

3. A point source of white light is located in close proximity to a reference. Describe the formation of colored interference fringes on the screen behind the reference. Describe the radii of the fringes that depend on the geometry of the system and the wavelength of the light.

4. Describe the time coherence property of the light source (3-4 sentences maximum).

5. A plane wave falls on a reference at right angles. The source generating the plane wave has a finite coherence time τc. Write down an approximate expression describing the passage through the reference. Hint: Why is the relationship between τc and d important? What is the physical meaning of this relationship?

6. Suggest a method for measuring the coherence of light with the Fabry-Perot standard. (Note: in practice, other interferometers are the preferred choice over this task). Bonus: suggest other interferometers that are more convenient to use to estimate source coherence properties.

Second term
Checking questions:
1. Formulate the laser generation equation
2. Design an optical resonator
3. Formulate the main characteristics of laser source
4. Describe the main processes of interaction between light and matter
5. Solve the velocity equations of laser amplifier
6. Derive laser generation threshold conditions
7. Calculate the Fabry-Perot resonator
8. Find the ABCD matrix for the optical system

Examples of exam papers:

Paper 1.

1. Llaser generation equations for one or many modes in the optical resonator. Homogeneous and inhomogeneous line broadening. Conditions for mode beating.

2. Formulation of light propagation in ray optics. ABCD matrix for basic optical elements. Analysis of optical elements using the ABCD matrix.

Paper 2.

1. Continuous and pulsed lasers, Q-switching and modelocking. Analysis of active laser generation media.

2. Solution of diffraction problem in the formulation of Gaussian beams. Basic properties of Gaussian beams. Propagation of Gaussian beams in optical circuits in the ABCD matrix formulation. Stability conditions of optical resonators.

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 a credit (9th term) and an exam (10th term). The questioning 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.