COURSE OUTLINE

(1) GENERAL

SCHOOL	School of Science		
ACADEMIC UNIT	Physics		
LEVEL OF STUDIES	Undergraduate		
COURSE CODE	**10YK501**	**SEMESTER**	**8**
COURSE TITLE	**QUANTUM OPTICS AND LASERS**		

INDEPENDENT TEACHING ACTIVITIES *if credits are awarded for separate components of the course, e.g. lectures, laboratory exercises, etc. If the credits are awarded for the whole of the course, give the weekly teaching hours and the total credits*	**WEEKLY TEACHING HOURS**	**CREDITS**
Lectures (theory and exercises)	4	6
Laboratory practice	* see unit (4)	

COURSE TYPE *general background, special background, specialised general knowledge, skills development*	Specialised Knowledge. (Roughly, around 1/2 of students who take the exam come from the Direction of Condensed Matter Physics, 1/3 from the Direction of Nuclear Physics and Elementary Particles and the rest from the other three Directions of the NKUA Department of Physics.)
PREREQUISITE COURSES:	No
LANGUAGE OF INSTRUCTION and EXAMINATIONS:	Greek
IS THE COURSE OFFERED TO ERASMUS STUDENTS	Yes, in the English language for Erasmus students
COURSE WEBSITE (URL)	e-class website: https://eclass.uoa.gr/courses/PHYS107

(2) LEARNING OUTCOMES

Learning outcomes

The course learning outcomes, specific knowledge, skills and competences of an appropriate level, which the students will acquire with the successful completion of the course are described.

Consult Appendix A

- *Description of the level of learning outcomes for each qualifications cycle, according to the Qualifications Framework of the European Higher Education Area*
- *Descriptors for Levels 6, 7 & 8 of the European Qualifications Framework for Lifelong Learning and Appendix B*
- *Guidelines for writing Learning Outcomes*

The aim of this course is to introduce students to -- and deepen their knowledge about -- the quantum aspect of the interaction of electromagnetic (EM) radiation - mainly near the visible regime - with matter, which is considered as a set of two-level or multi-level systems, as well as obtain a first contact with LASERs.

By successfully attending and completing the course, the student should:

- Become familiar with the first steps of quantum optics and understand how black body radiation and the experimental - theoretical convolution led to quantization. Compare the laws of Planck, Rayleigh-Jeans, Wien, and explain how the Stefan-Boltzmann law arises. Analyze EM waves with emphasis on boundary conditions and normal modes within a cavity (rectangular parallelepiped and cylindrical).

- Familiarize with the concepts of discrete spectrum, two-level system (2LS), multi-level system (mLS) and their various realizations in atoms, quantum dots, color centers. Understand the stimulated or spontaneous absorption and emission processes of a photon in the 2LS.
- Analyze the interaction of EM radiation - 2LS or mLS semi-classically, that is, treating the 2LS or mLS as a system of quantum states, while EM waves are treated classically within the dipole approximation. Become familiar with time-dependent perturbation theory. Understand concepts such as Rabi frequency, transfer rate, rotating wave approximation, and how the allowed transitions and the corresponding selection rules arise.
- Analyze the interaction of EM radiation - 2LS or mLS quantum mechanically, that is, addressing both 2LS or mLS and the EM waves quantum mechanically. Understand quantization of EM field and concepts such as spinors, commutators, anticommutators, transition dipole moment. Study in this context absorption and emission of photons. Compare the semi-classical with the full quantum mechanical approach.
- Become familiar with MATLAB by plotting equations describing the time-dependent occupation probability of states in the semi-classical and in the quantum mechanical approach and the photon population in the quantum mechanical approach.
- Understand the principles of LASER operation. Analyze and solve rate equations with two lasing and two auxiliary levels. Be introduced into concepts such as level lifetime, pumping, critical pumping, population inversion. Calculate the population of levels and the radiation density in the cavity by analyzing the rate equations analytically in the stationary state and numerically as a function of time. Also, in this context, be introduced into MATLAB. Analyze the longitudinal and transverse EM field modes in a cavity (rectangular parallelepiped and cylindrical). Become familiar with various types of LASERs.

If time permits, be introduced to topics such as density matrix, Fresnel equations, Brewster angle, total internal reflection, polarized beam emission.
It is implied, anyway, that all these are accompanied with the solution of relevant problems.

General Competences

Taking into consideration the general competences that the degree-holder must acquire (as these appear in the Diploma Supplement and appear below), at which of the following does the course aim?

Search for, analysis and synthesis of data and information, with the use of the necessary technology *Adapting to new situations* *Decision-making* *Working independently* *Team work* *Working in an international environment* *Working in an interdisciplinary environment* *Production of new research ideas*	*Project planning and management* *Respect for difference and multiculturalism* *Respect for the natural environment* *Showing social, professional and ethical responsibility and sensitivity to gender issues* *Criticism and self-criticism* *Production of free, creative and inductive thinking* *……* *Others…*

With successful completion and examination of the course, the aim is that the student acquires the following general competences and skills:

Search for, analysis and synthesis of data and information. Working independently. Criticism and self-criticism. Production of free, creative and inductive thinking. Analytical and synthetic thinking. Critical thinking. New Technology skills. Learning MATLAB programming language. Problem solving. Meeting Deadlines and Keeping Schedules (5 sets of problems and 3 MATLAB exercises are given to the students with deadlines).

(3) SYLLABUS

<u>Synoptically (Syllabus)</u>

- Black body. Planck, Rayleigh-Jeans, Wien, Stefan-Boltzmann laws.
- Electromagnetic (EM) waves: boundary conditions, normal modes in a cavity.
- Discrete spectrum. Two-level system (2LS) or multi-level system (mLS): atom, quantum dot, color center. Stimulated - spontaneous absorption and emission processes.
- EM radiation - 2LS or mLS interaction, semi-classically. Dipole approximation. Time-dependent

perturbation theory. Rabi frequency. Rotating wave approximation. Allowed transitions.

- EM radiation - 2LS or mLS interaction, quantum mechanically. EM field quantization. Spinors. Commutators. Anticommutators. Transition dipole moment. Photon absorption - emission. Density matrix.
- LASER: pumping, population inversion, rate equations. Longitudinal, transverse EM modes. LASER types.

Course Description

We focus on quantum optics, while we describe the LASER operation principles without extending to technical details. The modules taught are mainly:

Introduction to the quantum nature of light, i.e., black body, Planck, Rayleigh-Jeans, Wien, Stefan-Boltzmann laws, EM waves: boundary conditions, normal modes in a cavity. Infinitesimal number of EM wave normal modes per infinitesimal frequency interval.

Einstein mechanisms of interaction between EM radiation - matter (2LS). Stimulated and spontaneous absorption and emission processes. Derivation of Planck's law from the absorption and emission processes and Boltzmann statistics. Relation between Einstein coefficients A and B. Discrete spectrum: atoms and molecules, color centers, artificial atoms and molecules. Color centers. Quantum dots.

Semi-classical approach to the interaction between EM radiation - matter (2LS or mLS). EM field: classically, 2LS or mLS, e.g. atom or quantum dot: quantum mechanically. Unperturbed system (that is without EM field). Perturbed system (that is subjected to EM field). Time-dependent perturbation theory. Dipole moment. Equations describing the time evolution of a 2LS or mLS and their solution. Rabi frequency. Rotating Wave Approximation. Calculation of Einstein coefficients. Hydrogen atom. Calculation of the dipole moment matrix elements. Allowed and forbidden transitions. Selection rules.

Quantum mechanical approach to the interaction between EM radiation - matter (2LS or mLS). EM field quantization. EM field Hamiltonian with photon annihilation and creation operators. 2LS or mLS Hamiltonian with spinors. 2LS or mLS - EM field interaction Hamiltonian. Boson commutation and fermion anticommutation relations. Expected values of quantities for the Rabi and Jaynes-Cummings Hamiltonians. Photon absorption and emission.

Basic LASER operation principles. Pumping mechanisms. Rate equations with two lasing and two auxiliary levels. Level lifetime. Pumping. Relative probabilities. Radiation loss at mirrors. Rate equations for the lasing levels' populations and the radiation density in the cavity. Level populations and radiation density at the stationary case. Critical pumping. Population inversion. Various types of LASERs. Longitudinal and transverse EM field modes in a cavity (rectangular parallelepiped and cylindrical).

Other subjects: Fresnel equations. Brewster angle. Total internal reflection. Polarized beam emission. Density matrix. Issues relative to the properties and the operation of LASERs.

The course is partially renewed each year.

Keywords: electromagnetic (EM), photon, quantum of light, quantum optics, two-level system (2LS), multi-level system (mLS), EM field quantization, density matrix, electric transition dipole moment, Rabi frequency, EM radiation - matter interaction, commutators, anticommutators, bosons, fermions, stimulated and spontaneous Einstein mechanisms, semi-classical approximation, LASER, pumping, population inversion, EM field Hamiltonian with photon creation and annihilation operators, two-level and multi-level Hamiltonian with spinors, two-level and multi-level - EM field interaction Hamiltonian, boson commutation and fermion anticommutation relations, spinors, Rabi Hamiltonian, Jaynes-Cummings Hamiltonian, photon absorption, photon emission, quantum dots, color centers.

(4) TEACHING and LEARNING METHODS - EVALUATION

<table>
<tr><td>DELIVERY
Face-to-face, Distance learning, etc.</td><td>Face-to-face</td></tr>
<tr><td>USE OF INFORMATION AND COMMUNICATIONS TECHNOLOGY
Use of ICT in teaching, laboratory education, communication with students</td><td>Yes

Lessons are mainly taught on the greenboard (except, of course, during the pandemic), with encouragement of questions, observations and objections by the students. This is a constructive process. A projector is rarely used when it is necessary to display an image or a video.

There is e-mail communication with students.

There is a regularly renewed e-class website:
https://eclass.uoa.gr/courses/PHYS107/
Most examination papers of older examinations can be found, solved, there.

Video lectures can be found at https://delos.uoa.gr/
and various lectures at
https://www.youtube.com/@simserides

The e-book Quantum Optics and LASERS, open access for everybody, can be found at the Kallipos repository:
Κ. Σιμσερίδης [C. Simserides], 2015.
Κβαντική οπτική και LASERs [Quantum optics and LASERs]. Αθήνα [Athens]: Σύνδεσμος Ελληνικών Ακαδημαϊκών Βιβλιοθηκών [HEALLINK].
Γλώσσα [Language]: Ελληνικά [Greek]. Pages 324.
URI: http://hdl.handle.net/11419/2108
ISBN: 978-960-603-073-4 Eudoxus ID: 320166

This textbook will be published shortly: Quantum Optics - Κβαντική Οπτική (bilingual), C. Simserides - Κ. Σιμσερίδης, Kallipos,, 2023, Athens, (e-book).

There are 3 exercises, which must be solved by the students, by means of numerical calculations, in MATLAB. So, for one hour, I explain, in groups, in my office, what students have to do, in front of computers.

When possible, we visit a research laboratory of our Department where optical measurements are performed, with the help of a LASER, on semiconductor heterostructures.</td></tr>
<tr><td>TEACHING METHODS
The manner and methods of teaching are described in detail.
Lectures, seminars, laboratory practice, fieldwork, study and analysis of bibliography, tutorials, placements, clinical practice, art workshop, interactive teaching, educational visits, project, essay writing, artistic creativity, etc.

The student's study hours for each learning</td><td>
<table>
<tr><th>Activity</th><th>Semester workload</th></tr>
<tr><td>Lectures</td><td>42 hours</td></tr>
<tr><td>Exercises</td><td>10 hours</td></tr>
<tr><td>Individual Study/ Study and Analysis of bibliography / Preparation</td><td>90 hours</td></tr>
<tr><td>Laboratory practice *</td><td>Use of MATLAB. Numerical solution of 3 exercises.
8 hours</td></tr>
</table>
</td></tr>
</table>

activity are given as well as the hours of non-directed study according to the principles of the ECTS	Writing reports/ essays	After completion of each chapter, in total 5 sets of exercises, which count altogether one unit (1/10) in the final grade of the course, are given to all those students who desire such an option.
	Educational Visits	Visit to a research semiconductor laboratory in our Department, where optical measurements are performed with the help of a LASER.
	Course Total	**150 hours**

STUDENT PERFORMANCE EVALUATION *Description of the evaluation procedure* *Language of evaluation, methods of evaluation, summative or conclusive, multiple choice questionnaires, short-answer questions, open-ended questions, problem solving, written work, essay/report, oral examination, public presentation, laboratory work, clinical examination of patient, art interpretation, other* *Specifically-defined evaluation criteria are given, and if and where they are accessible to students.*	Final written exams in Greek with open-ended questions and problem solving. Writing essays: After completion of each chapter, in total 5 sets of exercises, which count altogether for one unit (1/10) in the final grade of the course, are given to all those students who desire such an option. Also, by use of MATLAB, numerical solution of 3 exercises.

(5) ATTACHED BIBLIOGRAPHY

- Suggested bibliography: *(title, author, publisher, year, place, Eudoxus code)*

0. This textbook will be published shortly: Quantum Optics - Κβαντική Οπτική (bilingual) , C. Simserides - Κ. Σιμσερίδης, Kallipos,, 2023, Athens, (e-book).

- Κβαντική Οπτική και Lasers [Quantum Optics and Lasers], Κ. Σιμσερίδης [C. Simserides], Kallipos, 2015, Athens, 320166 (e-book)
- Κβαντική Οπτική [Quantum Optics], M. Fox, ΙΤΕ Πανεπιστημιακές Εκδόσεις Κρήτης [Crete University Press], 2014, Ηράκλειο Κρήτης [Heraklion Crete], 32998376
- Εισαγωγή στη Κβαντική Οπτική και Lasers [Introduction to Quantum Optics and Lasers], Σ. Βες [S. Ves], Εκδόσεις Σ. Γιαχούδης & ΣΙΑ Ο.Ε, 1999, Θεσσαλονίκη [Thessaloniki], 8762
- Principles of Lasers (electronic resource), O. Svelto, HEAL-LINK, 2010, 73250879 (e-book)
- Αρχές των Lasers [Principles of Lasers], O. Svelto, Εκδόσεις Σ. Αθανασόπουλος & ΣΙΑ Ο.Ε., 1986, Αθήνα [Athens], 45477
- Laser, Π. Περσεφόνης [P. Persefonis], Εκδόσεις Π. Δενερτζής, 2010, Αθήνα [Athens], 27120

- Related academic journals: There are too many to cite here because Quantum Optics and LASERs are today at the cutting edge of science, in optics as well as in condensed matter physics with numerous interdisciplinary applications.