DOCTORAL STUDIES COURSE UNIT DESCRIPTION

Name of subject	Scientific Field	Faculty	Center/Institute/ Department
Interaction of laser radiation with matter (8 ECTS credits)	Physics N 002	Faculty of Physics Center for Physical Sciences and Technology	Laser Research Center Department for Laser Technics
Student's workload	Hours	Student's workload	Hours
Lectures		Consultations	8
Individual study	192	Seminars	

Course annotation

Characterization of laser radiation. Properties of laser radiation. Basic parameters describing laser radiation. Methods for measuring energy, temporal, spectral and spatial radiation parameters.

Electron in electromagnetic field. Energy of free electron oscillation. Radiation scattering by electron. Stop radiation and absorption. Electron motion in a heterogeneous oscillating field. Electron motion in a bonded system. Atomic oscillator. Atomic ionization.

Absorption of laser radiation. Absorption mechanisms in metals, dielectrics, semiconductors and plastics. Peculiarities of powerful laser radiation absorption. Dynamic change of irradiated material parameters.

Melting of irradiated surface. Temperature time distribution and maximum melt depth. Strong overheating. Hardening. Convection and surface deformation. Formation of glass structures.

Material removal. Evaporation from the laser illuminated area. Energy balance in the one-dimensional case. Stationary and non-stationary evaporation. Knudsen layer. Kickback pressure. Emission of particles from the surface of a material by exposure to laser radiation.

Plasma formation. Ionization. Optical properties of plasma. Physical phenomena that determine the properties of plasma at varying degrees of ionization. Laser-induced explosion and detonation waves. Plasma at very high intensities of laser radiation. Principles of laser breakdown spectroscopy.

Gas breakdown. Initiation and development of the breakdown. Laser spark. Spark radiation. Plasma formation by focusing laser radiation in the atmosphere.

Nucleation and clustering. Formation of droplets and clusters in laser evaporated material. Cluster formation in pulsed laser ablation. Nucleation and clustering on laser illuminated surfaces.

Laser ablation with nanosecond pulses. Ablation mechanisms. Thermal, photomechanical and photochemical ablation. Ablation threshold and rate. Material damage during ablation.

Peculiarities of ablation in the case of ultrashort pulses. Cases of short and long pulses. Photophysical and thermal ablation. Two-temperature model. Modeling of molecular dynamics. Comparison of ablation using nanosecond and femtosecond pulses.

Ripples on the surface of materials. Schemes for creation of ripples. Types of ripples. Mechanisms of ripples formation.

Peculiarities of powerful laser radiation absorption in transparent media. Multiphoton absorption. Avalanche ionization. Critical density of free carriers and its influence on laser radiation absorption. Laser damage to transparent materials.

Volume modification of transparent media by ultrashort pulses. Refractive index modifications. Formation of nanogratings. Void formation. Etching of modified areas. Physical mechanisms explaining modifications.

Complex beams in transparent media processing. Stealth dicing method. Bessel beam utilization schemes and advantages. Airy beam applications.

Petawatt power laser systems. Principles of petawatt power laser systems development. European Extreme Light Infrastructure (ELI). New possibilities in studying the interactions between radiation and matter with a petawatt laser system. Generation of high harmonics by illuminating hard surfaces with high intensity ultrashort pulses.

X-rays and acceleration of charged particles in laser plasma. X-ray generation in laser-generated plasma. Acceleration of electrons and ions in laser-generated plasma.

Thermonuclear reactions initiated by powerful laser pulses. Schemes used. Initiation mechanisms.

List of literature

1. M. von Allimen, A. Blatter, *Laser-Beam Interactions with Materials: Physical principles and Applications,* 2nd updated ed. Springer Series in Materials Sciences, Springer-Verlag Berlin 1995.

2. P. Schaaf , *Laser Processing of Materials*, Fundamentals, Applications and Developments, 2010, Springer-Verlag Berlin Heidelberg.

3. K. Sugioka, *Handbook of Laser Micro- and Nano-Engineering*, Springer, Cham, 2020, (ISBN: 978-3-319-69537-2).

4. R.D. Schaeffer, *Fundamentals of laser micromachining*, CRC Press, 2012, 238 p. (ISBN: 978-1-4398-6084-7).

5. M.Wegener, *Extreme nonlinear optics*, Springer, 2005. – 223 p. (ISBN: 3-540-22291-X).

6. P.M. Ossi, *Advances in the Application of Lasers in Materials Science*, 1st ed., Springer Series in Materials Science Book 274, Springer Nature Switzerland AG, 2018, 395 p.,(ISBN 978-3-319-96844-5).

List of additional literature

1. M.Fox, *Optical Properties of Solids,* 2nd ed., Oxford University Press, New York, 2010.- 416 p.

2. S. Nolte, F. Schrempel, F. Dausinger, *Ultrashort Pulse Laser Technology*, Springer, 2016, 358 p. (iSBN: 978-3-319-17658-1).

3. R. Osellame, G. Cerullo, R. Ramponi (Eds.), *Femtosecond Laser Micromachining*, Springer, 2012, 483 p. (ISBN: 978-3-642-23365-2).

4. D. Bauerle *Laser Processing and Chemistry,* 3rd Edition, Springer 2000 788 p. (ISBN: 3-540-66891-8).

5. *Laser ablation and its applications*, Ed. C.Phipps, Springer, 2007. – 597 p. (ISBN: 978- 0-387-30452-6).

6. R.M.Wood "*Laser- Induced Damage of OpticalMaterials*" IOP Publishing Ltd, Bristol, 2003, - 241 p., (ISBN: 0 7503 0845 1).

7. 6. F.X.Kärtner, *Few-Cycle Laser Pulse Generation and its Applications*, Springer, 2004. – (ISBN: 3-540-20115-7).

Subject presentation and method of payoff

There are no lectures on the subject. Doctoral students have to learn from the textbooks themselves. Part of this course is taught in the 1st semester at Vilnius University Physics Faculty in the Laser Technology program for master's students, so sometimes doctoral students from other universities or other programs choose to listen to part of those lectures together with current master's students. The subject section includes consultations, the topics of which are offered by the doctoral students who have chosen the course.

The exam consists of two parts. The first is the preparation of a paper that reviews a certain topic of the interaction between laser radiation and matter, which is important for the preparation of a doctoral dissertation. Its volume is > 40 000 signs. Efforts are made to select the topic of the paper in such a way that its material is useful for the review of the dissertation and the work carried out in it. The content of the paper is first offered to the doctoral student together with his / her research supervisor, and then coordinated with the consulting lecturers.
After agreeing on the content of the paper, the doctoral student prepares the paper and forwards it to the consulting lecturers, who are included in the examination commission. Then a time is set when the presentation of the paper takes place and the doctoral student has to prepare the presentation which takes ~ 20 minutes. The presentation is presented to at least 3 members of the examination commission. After the presentation, the questions of the commission members are answered. The paper and its presentation with the answer to the questions can be evaluated with a maximum of 5 points.
The second part of the exam is the written answers to 3 questions. To do this, are given 1.5 hours. Typically, a list of 10-15 generalized questions is compiled, based on the topics in the stock, from which those 3 questions are selected. Once the doctoral students have written the answers, they are scanned and forwarded to all members of the examination board, who must evaluate them. Written answers to 3 questions can be evaluated with a maximum of 5 points.
The evaluation of each member of the examination commission, both for the paper and its presentation, as well as for the answers to the given questions, is averaged and the final summary evaluation with a maximum value of 10 points is recorded accordingly.

Consulting teachers	Scientific degree	Pedagogical name	Main scientific works published in a scientific field in last 5 year period
Vytautas Jukna (vytautas.jukna @ff.vu.lt)	Dr.	Assoc. Prof.	1. E. Kažukauskas, S. Butkus, P. Tokarski, V. Jukna, M. Barkauskas, V. Sirutkaitis, Micromachining of transparent biocompatible polymers applied in medicine using bursts of femtosecond laser pulses, Micromachines 11 (12), 1093 (2020) 2. R. Grigutis, G. Tamošauskas, V. Jukna, A. Risos, A. Dubietis, Supercontinuum generation and optical damage of sapphire and YAG at high repetition rates, Opt. Lett. 45 4507-4510 (2020) 3. S. Butkus, V. Jukna, D. Paipulas, M. Barkauskas, V. Sirutkaitis, Micromachining of Invar Foils with GHz, MHz and kHz Femtosecond Burst Modes, Micromachines 11 733 (2020) 4. A. Marcinkevičiūtė, V. Jukna, R. Šuminas, N. Garejev, G. Tamošauskas, A. Dubietis, Supercontinuum generation in the absence and in the presence of color centers in NaCl and KBr, Results Phys. 14 102396 (2019) 5. Q. Liang, Y. Zhong, Z. Fan, H. Diao, V. Jukna, W. Chen, A. Houard, Z. Zeng, R. Li, Y. Liu, Optical transmission during mid-infrared femtosecond laser pulses ablation of fused silica, Appl. Surf. Sci. 471 506-515 (2019)

Gediminas Račiukaitis (g.raciukaitis@ftmc.lt)	Dr.		1. K. A. Drogowska-Horna, I. Mirza, A. Rodriguez, P. Kovaříček, J. Sládek, T. J.-Y. Derrien, M. Gedvilas, G. Račiukaitis, O. Frank, N. M. Bulgakova, M. Kalbáč, Martin. Periodic surface functional group density on graphene via laser-induced substrate patterning at Si/SiO_2 interface // Nano Research. 2020, vol. 13, iss. 9, pp. 2332-2339. 2. J. Dudutis, J. Pipiras, S. Schwarz, S. Rung, R. Hellmann, G. Račiukaitis, P. Gečys, Laser-fabricated axicons challenging the conventional optics in glass processing applications // Optics Express. 2020, vol. 28, no. 4, pp. 5715-5730. 3. E. Markauskas, L. Zubauskas, G. Račiukaitis, P. Gečys, Damage-free patterning of thermally sensitive CIGS thin-film solar cells: Can nanosecond pulses outperform ultrashort laser pulses? // Solar Energy. 2020, vol. 202, p. 514-521. 4. K. Ratautas, A. Jagminienė, I. Stankevičienė, M. Sadauskas, E. Norkus, G. Račiukaitis, Evaluation and optimisation of the SSAIL method for laser-assisted selective electroless copper deposition on dielectrics // Results in Physics. 2020, vol. 16, art. no. 102943. 5. V. Tomkus, V. Girdauskas, J. Dudutis, P. Gečys, V. Stankevič, G. Račiukaitis, I. Gallardo González, D. Guénot, J. B. Svensson, A. Persson, O. Lundh, Olle. Laser wakefield accelerated electron beams and betatron radiation from multijet gas targets // Scientific Reports. 2020, vol. 10, art. no. 16807.
Andrius Melninkaitis (andrius.melninkaitis@ff.vu.lt)	Dr.	Doc.	1. Linas Smalakys and Andrius Melninkaitis, "Predicting lifetime of optical components with Bayesian inference," Opt. Express 29, 903-915 (2021) 2. Balys Momgaudis, Viaceslav Kudriasov, Mikas Vengris, and Andrius Melninkaitis, "Quantitative assessment of nonlinearly absorbed energy in fused silica via time-resolved digital holography," Opt. Express 27, 7699-7711 (2019) 3. Balys Momgaudis, Stephane Guizard, Allan Bilde, and Andrius Melninkaitis, "Nonlinear refractive index measurements using time-resolved digital holography," Opt. Lett. 43, 304-307 (2018) 4. Tomas Tolenis, Lina Grinevičiūtė, Rytis Buzelis, Linas Smalakys, Egidijus Pupka, Simas Melnikas, Algirdas Selskis, Ramutis Drazdys,

			and Andrius Melninkaitis, "Sculptured anti-reflection coatings for high power lasers," Opt. Mater. Express 7, 1249-1258 (2017) 5.Tomas Tolenis, Lina Grinevičiūtė, Linas Smalakys, Mindaugas Ščiuka, Ramutis Drazdys, Lina Mažulė, Rytis Buzelis and Andrius Melninkaitis, "Next generation highly resistant mirrors featuring all-silica layers" Sci Rep 7, 10898 (2017). https://doi.org/10.1038/s41598-017-11275-0
Mindaugas Gedvilas (mindaugas.gedvilas@ftmc.lt)	Dr.		1. A. Žemaitis, M. Gaidys, P. Gečys, M. Gedvilas, Influence of nonlinear- and saturable-absorption on laser lift-off threshold of oxide/metal structure, Opt. Lett. 45, 6166 (2020). 2. A. Žemaitis, A. Mimidis, A. Papadopoulos, P. Gečys, G. Račiukaitis , E. Stratakis, M. Gedvilas, Controlling the wettability from highly-hydrophilic to superhydrophobic of stainless steel by femtosecond laser-induced ripples and nanospikes, RSC Advances 10, 37956 (2020). 3. A. Žemaitis, J. Mikšys, M. Gaidys, P. Gečys, M. Gedvilas, High-efficiency laser fabrication of drag reducing riblet surfaces on pre-heated Teflon, Mater. Res. Express 6, 065309 (2019). 4. A. Žemaitis, M. Gaidys, P. Gečys, G. Račiukaitis, M. Gedvilas, Rapid high-quality 3D micro-machining by optimised efficient ultrashort laser ablation, Opt. Lasers Eng. 114, 83-89 (2019). 5. A. Žemaitis, M. Gaidys, M. Brikas, P. Gečys, G. Račiukaitis, M. Gedvilas, Advanced laser scanning for highly-efficient ablation and ultrafast surface structuring: experiment and model, Sci. Rep. 8, 17376 (2018).
Julius Vengelis (julius.vengelis@ff.vu.lt)	Dr.	Doc.	1. J. Banys, J. Pimpė, O. Balachninaitė, V. Jarutis, J. Vengelis, Non-destructive periodic poling quality evaluation of MgO:PPLN and Rb:PPKTP crystals based on crystal translation and parametric light generation, Optik 277, 170686 (2023). 2. J. Banys, J. Savickytė, O. Balachninaitė, S. Armalytė, V. Tamulienė, V. Jarutis, J. Vengelis, Performance investigation of high-efficiency widely tunable subnanosecond optical parametric generator and amplifier based on MgO:PPLN, Optics Express 30(13), 459826 (2022).

			3. G. Stanionytė, E. Vėjalytė, V. Tamulienė, V. Jarutis, J. Vengelis, Subnanosecond widely-tunable in the visible spectrum range LBO based optical parametric amplifier, Journal of Optics 24(4), 045506 (2022). 4. J. Banys, J. Vengelis, Efficient single-pass and double-pass pre-chirp managed Yb-doped rod-type fiber amplifiers using Gires–Tournois interferometric mirrors, Optik 249, 168185 (2022). 5. J. Vengelis, G. Sinkevičius, J. Banys, L. Masiulis, R. Grigonis, J. Domarkas, V. Sirutkaitis, Investigation of piezoelectric ringing effects in Pockels cells based on beta barium borate crystals, Applied Optics 58(33), 9240-9250 (2019).
Certified during Doctoral Committee session 23/11/2023, protocol No. (7.17 E) 15600-KT-508			
Committee Chairman prof. S. Juršėnas			