

## Laser Processing and laser characterization

3 ECTS

UJM semester 3

### Part 1: Laser processes for material structuring

**Course instructor:** Ass. Prof. **Ciro D'Amico (UJM), Sedao (UJM), Yves Jourlin (UJM)**

**Language of instruction:** English

2 ECTS

#### Overview

Nowadays laser materials processing is playing an important role in the modern manufacturing industry and economy. While laser cutting, welding, marking and drilling processes have reached maturity with wide industrial acceptance, new developments in recent years in additive manufacturing and micro/nano fabrication have enabled new capabilities that lasers can bring to the manufacturing industry. With the availability of high intensity lasers such as femto- and pico-second lasers, new beam material interaction phenomena appear and with them new technology developments and new research. Today concepts of optimization, modelling/simulation, and understanding the basic science involved play a critical role in advanced laser materials processing science and technology.

The course will give an overview of the so called “Direct Laser Writing (DLW)” techniques used for structuring and functionalizing materials (surface and bulk) on micro and nano-scales. It is strongly focused on ultra-short lasers, although some examples of material structuring by longer duration (nanoseconds) laser pulses will be presented. A theoretical and phenomenological description of laser-matter interaction processes will be given at the beginning. Techniques used to tailor the beam properties will be described. They are actually quite important to control laser processes.

#### Learning outcomes

On successful completion of this course, students should have the skills and knowledge to:

- Understand and master basic knowledge of laser-matter interaction at high intensities;
- Understand and master the concept of laser material structuring and its applications;
- Understand the mechanisms that govern the functionalities of the different micro- and nano-structured surfaces and their potential applications;
- Learn about the different methods of fabrication and characterization of micro- and nano-structured surfaces.
- To be able to identify the most appropriate fabrication technologies depending on the requirement on the micro- and nano-structured surfaces
- Critically review and assess scientific literature in the field;

#### Content

- Ultrashort laser pulses and their manipulation
  - Concept of temporal and spectral phase, intensity and spectrum of a laser pulse.
  - Temporal and spatial laser pulse shaping.
- Basics of laser-material interaction at high intensities
  - Nonlinear ionization phenomena
  - Laser-plasma interaction
  - Relaxation phenomena and thermodynamics

- Laser material processing
  - Basics concepts of laser-induced local material modifications
  - Difference between femtosecond and nanosecond laser pulses for material structuring
  - Laser material structuring with spatially and temporally shaped laser pulses
  - Applications to surface engineering
  - Applications to integrated photonics

### Teaching methods

- Lectures: 10 hours
- Tutorials: 10 hours
- Practical work: 12h [MANUTECH USD, NANOSAINTE]

### Study materials

- Lecture PPT slides (UJM website CLAROLINE)
- Tutorials and previous year's exams with solutions (UJM website CLAROLINE)
- Scientific articles and reviews (UJM website CLAROLINE)

### Assumed Knowledge

- Basics of Electromagnetism, Nonlinear Optics, Solid State Physics, Planar waveguides, Laser physics, Matlab, Diffraction gratings

## Part 2: Temporal and spatial shaping of the laser pulse

**Course instructor: Ass. Prof. F. Bourquard**

**Language of instruction: English**

**1 ECTS**

### Overview

As has been seen in part 1, due to their unique temporal and spectral properties, ultrashort pulses interact with matter on a time scale shorter or comparable to the characteristic durations of energy relaxation: electron-phonon coupling, heat diffusion, pressure shockwaves, expansion etc. There is thus a strong interest in controlling the temporal distribution of the laser energy in order to play with the different phenomena taking place.

The goal of this course is to explore the different methods for modifying the temporal shape of a pulse, such as classic interferometers to generate multiple pulses, grating pairs or prisms to generate longer pulses, or Fourier synthesis methods based on 4f-setup in zero-dispersion configuration to obtain any temporal shape. An emphasis will also be put on the measure and characterization of the obtained pulses, exploiting non-linear interaction for auto- or cross-correlation, with or without spectral characterization (FROG).

Following lectures on the subject, the student will simulate Fourier-synthesis using a python code that they will enhance and exploit.

### Learning outcomes

- Understanding the temporal and spectral properties of ultrashort pulses

- Knowing and understanding the different pulse shaping techniques
- Knowing and understanding the different ultrashort pulses characterization techniques

## **Content**

- Ultrashort laser pulses characteristics, temporal, spectral, phase properties
- Different techniques for modifying pulses:
  - Interferometry
  - Grating pairs, prisms, etc.
  - Fourier synthesis
- Different techniques for measuring pulses:
  - Non-linear auto- and cross correlatioin
  - FROG based techniques
  - Etc.
- Simulation of ultrashort pulses and modeling of their travel and shaping
  - Writing and using a code creating the pulse and its Fourier-transform
  - Applying new spectral phases to obtain new pulse shapes

## **Teaching methods**

- Lectures: 6 hours
- Tutorials: 6 hours

## **Study materials**

- Pen and paper, teaching on the board
- Lecture-tutorial guide
- Relevant scientific articles and reviews

## **Assumed Knowledge**

- Similar as Part 1

## **Evaluation criteria for the whole course**

- Written exam 80%
- Lab session 20%

### **Part3: Analytical instrumentation**

**Course instructors: Ass. Prof. Dr. A. Morana, Dr. R. Stoian**

**Language of instruction: English**

**3 ECTS**

#### **Overview**

Interaction between light and matter is at the origin of spectacular phenomena driving chemical, physical, morphological and topographical material changes, being at the base of acquiring novel properties and evolution paths. Multiple physical and chemical processes concur to material transformation, their timescales being determinant for the evolution of matter.

The objective of this course is to give an overview of time-resolved optical investigation techniques capable of visualizing the material evolution in real time. These are able to probe materials under light exposure from strong field non-equilibrium excitation to thermodynamic and thermomechanical relaxation. We will introduce various concepts of time-resolved probing of matter active of multiple timescales including ultrafast phenomena. We will explore techniques detecting electronic and structural responses of matter in various optical ranges using spectroscopy and imaging.

#### **Learning outcomes**

On successful completion of this course, students should have the skills and knowledge to:

- Understand and master basic knowledge, theories and methods related to material transformations under light exposure; linear and nonlinear interactions, electronic, structural and thermodynamic relaxation paths
- Understand and master basic knowledge, theories and methods related to detection techniques based on spectroscopy and microscopy
- Identify, formulate and solve practical problems related to the use of time-resolved detection systems;
- Critically review and assess scientific literature in the field and apply knowledge to identify the novelty and practicality of proposed methods.
- Design and develop practical and innovative time-resolved investigation techniques.

#### **Content**

- Elements of linear and nonlinear optics: light propagation
- Light matter interaction: linear and nonlinear absorption, scattering phenomena
- Elements of optical spectroscopy
- Elements of vibrational spectroscopy
- Elements of THz spectroscopy
- Elements of microscopy (optical, electron microscopy)
- Time-resolved detection: pump-probe experiments
- Sources, techniques, and detectors
- Detecting ultrafast phenomena; optical methods,
- Detecting ultrafast phenomena; X-ray and electron diffraction methods
- **Introduction in femtosecond and attosecond spectroscopy and imaging**
- Case study 1: Electronic dynamics in molecules
- Case study 2: Electronic dynamics in condensed matter
- Case study 3: Plasmonics and plasmon interferometry

- Case study 4: Structural dynamics in solids.
- Case study 5: **Thermodynamic and thermomechanical response**
- **Case study 6: Topography response**

### Teaching methods

- Lectures: (20) hours
- Project work: (10) hours

### Study materials:

- S. Mukamel, Principles of Nonlinear Optics and Spectroscopy. New York: Oxford University Press (1995)
- T. Elsaesser, S. Mukamel, M. M. Murnane, N. F. Scherer, Ultrafast Phenomena XII. Berlin: Springer (2000).
- A. Zewail, Femtochemistry: Ultrafast Dynamics of the Chemical Bond Vol I,II, World Scientific Pub Co Inc (September 1, 1994)
- D. L. Andrews, A. A. Demidov, An Introduction to Laser Spectroscopy, Springer (2002)
- P. Balling and J. Schou, Femtosecond-laser ablation dynamics of dielectrics: basics and applications for thin films, Rep. Prog. Phys. 76 036502 (2013)
- M. Wollenhaupt, A. Assion, and T. Baumert, Femtosecond Laser Pulses: Linear Properties, Manipulation, Generation and Measurement. In Springer Handbook of Lasers and Optics, Ed. F. Träger, 937-983 (Springer Science and Business Media 2007).
- J. Diels and W. Rudolph: Ultrashort laser pulse phenomena Elsevier 2007
- R. W. Boyd: Nonlinear Optics (Academic Press 2008)
- R. Trebino, Georgia Institute of Technology: <http://www.frog.gatech.edu/talks.html>
- S. Agnello et al., Spectroscopy for Materials Characterization, Wiley, 2021
- W. Withayachumnankul and M. Naftaly, Fundamentals of Measurement in Terahertz Time-Domain Spectroscopy, J Infrared Milli Terahz Waves, 2014
- K. Reimann, Table-top sources of ultrashort THz pulses, Rep. Prog. Phys. 70, pp. 1597–1632, 2007
- M. T. Postek et al., Scanning Electron Microscopy: A Student's Handbook, Ladd Research Ind., Inc Williston, VT, 1980

### Assumed Knowledge

- Knowledge of geometrical optics, physical optics, electromagnetism, solid state physics, quantum mechanics, atomic and molecular physics

### Evaluation criteria

- Project work 50%
- Seminar/project presentations 50%

