Master Laboratory Physics

Nonlinear Optical Effects in Materials using Ultrashort Pulsed Lasers and its Applications in Photovoltaic Research

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Fraunhofer
ISE

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1 Safety Notes and Experimental Setup

1.1 Safety Notes

- **Always use the laser safety goggles**, when operating the laser! The laser is a class 4 laser system. It can permanently blind you for the rest of your life in femtoseconds.
- The **Laser device lights up blue**, indicating that the laser diodes are running, but you cannot see this with the safety goggles! If you see the laser head illuminated blue, you are in immediate danger!
- **Never look into the beam.** Never have your head in the height of the beam. Never put reflecting objects into the beam path. Do not wear jewelry (rings, watches, etc.): they could reflect the laser beam. Even the reflection is powerful enough to permanently blind you.
- Always make sure you know where the beam goes: never leave it unblocked, traveling though the room. The beam must never leave the optical table. When you remove a beam block, make sure there is a second block further down the beam path.
- Do not put paper or other **flammable objects** on the optical table. The laser has enough power to start a fire.
- Use the **laser emergency off** switch in case of doubt. It immediately shuts off the laser and only the laser, without damaging it. Do not hesitate to use it.
- Never leave the laser running unattended. When you leave the room, the laser must be off.
- Do **not change any cabling** on the laser system. Otherwise, the laser may exceed its maximum power or may be damaged! Do not touch the cabling: high voltage. Do not touch the optical fibers: the thin glass core is fragile and can break easily.
- Always follow the checklist for switching the system on and off.
- Do not touch any glass surface, lenses, mirrors, or other optical components. Not even with gloves. Keep the optics clean. Dirty optics can absorb the laser, heat up, and break, guiding the beam in unexpected directions. Cover the optics with the provided plastic cups if you do not use them.
- Block the laser before it enters the spectrometer, beam profiler, power meter or fiber unless you need it for the experiment!
- Ensure all optical components are securely mounted to prevent accidental misalignment.
- Verify the alignment of the laser beam path before starting any experiment!
- Keep the laboratory area organized and free of unnecessary items to prevent accidents.
- Follow all laboratory safety protocols and guidelines provided by the institution and the posed rules.
- Report any equipment malfunctions or safety concerns to the lab supervisor immediately.

1.2 Check List - Starting Amplitude Laser System

1. Switch on **cooling system** by pressing 'arrow up' button
2. **Switch on Power supplies**
   - First, switch on bottom controller
   - Then, switch on top controller
3. Open Amplitude Software
   (a) **Open Software** 'Driver Fibre TF'
   (b) Navigate to the tab **'Settings'**
      i. select **'COM2'** as the Port
      ii. select 'C:\Program Files [. . .] **Backup**.ini' as INI Settings
      iii. Ensure the numbers at 'Firmware', 'Current ID', . . . on the right-hand side are non-zero to confirm the connection, otherwise reboot the Software/PC and try again as the connection is not very stable!
   (c) Navigate to the tab **'Synchronisation'** and on the right side put on...
      - PP Mode to Pulse Picker
      - MOD Mode to Modulation
      - Trigger Option to MOD
      - Trigger to EXT
      - Gate to INT
   (d) Navigate to the tab **'LASER'** and check that **no red error indicatros** are present on the right-hand side
4. **Turn the key** to initiate the laser system
5. **Safety reminder:** At this point, you should close the chain and put on the laser safety goggles at the very latest!!!
6. **Press the start Button** at the tab 'LASER'

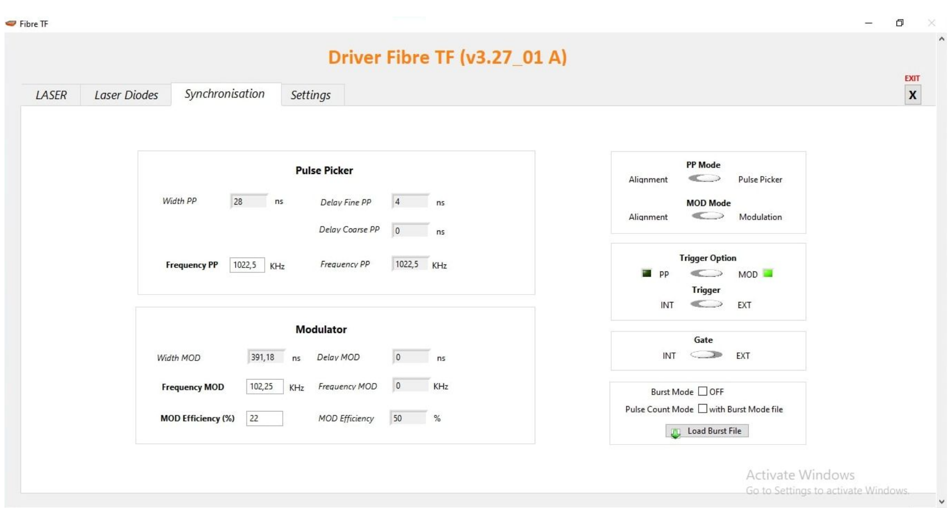

Figure 1: Screenshot of the laser control software.

1.3 Check List - Shut Down Laser System

Roughly the reversed order of 1.2.

1. **Press the start Button again** at the tab 'LASER'
2. Wait a few seconds until the laser is shutting down, then you can take off your goggles. If the laser device is still lighting up blue the laser is still running! Take care!
3. **Switch off the Key to 'Standby'**
4. It's up to you to **close the software program**.
5. If you've closed the software, then **switch off the power supplies**
   - First, switch off top controller
   - Then, switch off bottom controller
6. **Switch off cooling** system by pressing the 'arrow up' button again.

1.4 Leaving the Lab

- Make sure that **all used equipment is turned off**
  1. Shut down the **Laser System**
  2. Shut down the **PC** and **other devices**
  3. Put used **tools** back in place
  4. Switch off the **lights** and close the **door**
- Do not leave personal belongings in the lab and keep the lab clean
- Let us know when you leave

2 Motivation

This advanced lab course is designed to provide students with hands-on experience in working with ultrafast laser systems and understanding their applications in material processing and nonlinear optics. The course will cover theoretical principles, experimental setups and various measurement techniques, allowing students to connect theory with practice.

- **Familiarization with the Femtosecond Laser System**: Gain an understanding of the components and operation of the femtosecond laser system, including basic startup, shutdown procedures and handling optics and optomechanical components.
- **Characterization of Laser Beams**: Learn to measure and analyze laser beam properties, including power calibration, beam profiling using the knife-edge method.
- **Optical System Setup**: Develop skills in assembling and aligning an optical system using lenses, mirrors, beam splitter cubes, and waveplates to control the laser beam's polarization.
- **Non-Linear Conversion for Harmonics Generation**: Gain experience in setting up a system for second and third harmonic generation using BBO crystals, including the characterization of the resulting beams with a spectrometer.
- **Optical System for Material Processing**: Design and implement a system for laser material processing, including calculating Gaussian beam propagation parameters, selecting appropriate focusing lenses, and performing initial tests on sample materials.
- **Laser Ablation Fluence Threshold Determination**: Conduct experiments to determine the laser ablation fluence threshold on various materials, including silicon wafers, glass, and photovoltaic layers. This involves setting up the optical system, performing laser ablation, and analyzing the results using optical microscopy and data analysis software. Additionally, experiments will be conducted using wavelengths generated through nonlinear conversion.

Safety Note

Familiarize yourself with the safety notes in section 1 before the lab course. The used laser system is a class 4 laser system capable of causing permanent eye damage and vision loss. You will be questioned about the safety protocol before the start of the course.

3 Theory

Before starting the lab course, familiarize yourself with the topics listed in this section. Be prepared to explain the general concepts and keywords. Look up and understand how to convert the quantities and units. Tje following topics will be discussed before the beginning of the experiment.

3.1 Principles of Laser Systems

Familiarize yourself with the basic operation of laser systems. Understand the key components, including the laser gain medium, population inversion and the mechanisms that lead to stimulated emission.

Keywords: *Pulsed lasers, Fiber laser, Diode Pumped Solid State (DPSS) Laser, laser oscillator, laser amplifier, general structure of a laser system*

3.2 Characteristics of a Laser Beam

Study the essential properties of laser beams, including coherence, monochromaticity, directionality, beam profile and gaussian beam optics. Understanding these characteristics will be critical for the tasks you will perform.

Keywords: *gaussian beam, wavelength, pulse energy, average laser power, pulse duration, laser peak power, pulse frequency, beam diameter, laser intensity, laser fluence, focusing a beam using lenses, focal length, calculation of beam waist*

3.3 Knife Edge Method

Learn the knife edge method, which is a technique used to determine the beam waist and profile of a laser beam. The laser beam is directed onto a power meter. In front of the power meter, a sharp object is inserted partly into the beam in order to block a fraction of its power. The object is translated perpendicular to the beam, and the transmitted power P(k) is recorded as a function of the object translation k.

Think about: *How do you derive P(k)?*

3.4 Second Harmonic Generation

Familiarize yourself with the process of second harmonic generation (SHG), which involves the frequency doubling of light through nonlinear optical interactions. This process is essential for applications that require specific wavelengths.

Keywords: *Second Harmonic Generation, frequency doubling, phase matching, nonlinear optics*

3.5 Laser Material Processing

Gain insight into the various applications of lasers in material processing, including cutting, engraving, and ablation. Understanding the interaction between laser light and materials is crucial for the experiments you will perform.

Keywords: *cutting techniques, engraving methods, ablation threshold, material properties, heat affected zone*

3.6 Liu-Test

Understand the Liu test, a method used to determine the fluence threshold for laser ablation. This involves measuring the minimum energy density required to induce material removal, which is critical in assessing material suitability for laser processing.

Keywords: *fluence threshold, energy density, material removal rate, ablation efficiency*

3.7 Z-Scan

Study the principle of the Z-scan technique, which is employed to characterize the nonlinear optical properties of materials. This method involves moving the sample through the focus of a laser beam and measuring the transmitted intensity as a function of the position.

Keywords: *nonlinear refractive index, nonlinear absorption coefficient, closed aperture measurement, open aperture measurement, intensity profile*

4 Tasks

4.1 Familiarization with the laser and optical components

Component Identification: Identify all relevant components in the optical setup, including optomechanical components, mirrors, lenses, irises, shields, power meter, BBO crystal, filters and the laser.

Startup and Shutdown Procedures: Perform the startup and shutdown procedures of the laser system under supervision, ensuring that you understand the functions of the external laser control box.

Beam Alignment: Utilize a pair of irises to align the laser beam through their centers. Consider the degrees of freedom required for proper alignment. Adjust the angle and position of the beam as necessary, identifying the number of components needed for efficient alignment. There are numerous tutorials on laser alignment, for example from Thorlabs "How to Align a Laser — Thorlabs Insights".

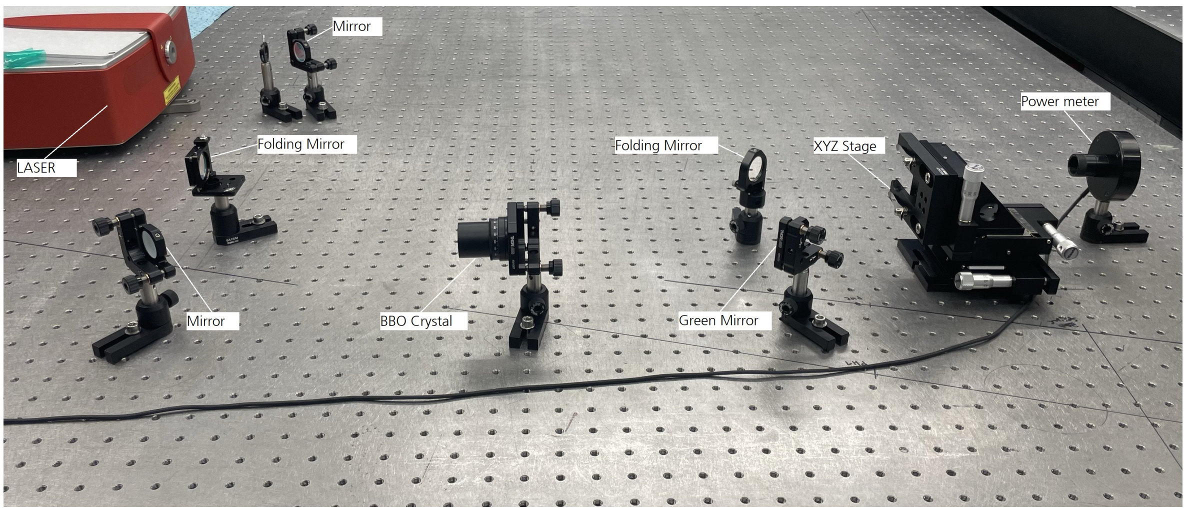

Figure 2: An example photo of how the experimental setup could be constructed. Keep in mind that this is just an example. There are many ways that one could assemble the optical setup to perform the experiments.

4.2 Characterization of the laser beam

Power calibration: The laser is controlled by the external laser control box. A potentiometer on this box allows to set a constant control voltage of 0V - 5V to the laser system. This voltage controls an internal acoustoptical modulator, which controls the average laser power. However, the transfer function from the control voltage to the laser power is highly nonlinear. Place a power meter into the beam path. Connect the power meter to the PC and open the Ophir software. On the left side, you can adjust the settings of the power meter: With the option "laser" you can set the calibration of the corresponding laser wavelength ($<$ or $>$ 800nm). The "range" option allows you to set the closest power range you expect during the measurement. Use the power meter to calibrate the laser control voltage. Plot the average laser power as a function of the control voltage.

Beam diameter: The provided 3D translation stage has three micrometer screws for fine adjustment of the stage's position in all dimensions. Mount a silicon wafer to the translation stage such that it is perpendicular to the laser table. Use this configuration to perform the knife edge method. Move the wafer all the way out of the laser beam and record the power. Insert the wafer partly into the beam, note the wafer's position k and the transmitted power P. Repeat, until you fully block the laser beam. Record at least 30 positions and powers. Derive the expected function $P(k)$ for a gaussian laser beam. Plot the measured $P(k)$ and fit your theoretical function. From the fit, you will obtain the beam diameter ω.

4.3 Nonlinear Conversion for Harmonics Generation

Incorporating BBO Crystal: Integrate the BBO crystal into the optical setup, utilizing specially designed reflective mirrors to optimize the configuration. Make sure you choose the right mirrors, as they are optimized for a specific wavelength (see the code written on the optical component). Evaluate if the existing optical structure can be adapted effectively to accommodate the new components. Design an optical system that allows for beam path switching by adjusting the mirrors. Ensure that the setup is flexible for various experimental needs. Use the power meter to find the best setting of the Rotation of the BBO Crystal.

Power calibration: Calibrate the newly added beam path as it was done before to ensure accurate measurements and optimal performance.

Beam diameter: Determine the beam waist of the added beam path using appropriate measurement techniques.

4.4 Laser Ablation Fluence Threshold Determination

Liu Test Execution: After the focus point of the lens has been found, the oxide layer on the surface can now be removed with laser pulses. The goal is to find the fluence threshold for laser ablation for glass and silicon wafers for each beam path. For this purpose, light pulses with varying energy are sent to the material to be examined. Use the Pulse mode of the external laser control box. For better statistics, several ablation points must be taken per pulse energy (approx. 5). Ensure a systematic approach for ablation.

Results Analysis: With the help of the light microscope and the 'Micro Manager' software, images of the laser modified area are taken, processed and evaluated. For the evaluation you can use the ImageJ software in such a way that the laser modified area is quantitative determined.

Data Plotting and Fitting: Plot the average area as a function of the pulse energy, where the energy is scaled logarithmically and perform curve fitting to determine the fluence threshold accurately for each beam path.

Think about: *Which measurement intervals are useful with regard to linearization and semi-logarithmic application of energy?*

Hint for using Micro Manager: *You can select the magnification factor of the micro-scope, which automatically scales the pixel size*

Hint for using ImageJ:

- *Choose Image: File → Import → Image sequence or File → open(recent)*
- *Process → Filters → Gaussian Blur → Default → 4,0 or higher*
- *Image → Crop*

- *Image → Adjust → Auto Threshold → default*
- *Analyze → Analyze Particles → limit size and circularity*

4.5 Z-Scan Measurement

Increasing Power Density: To enhance the power density of both beam paths, strategically incorporate a suitable lens into the optical structure. The goal of this part is to find the position x of the focal point, where the transmitted power P is the lowest.

Conducting Z-Scan Measurements: Perform Z-scan measurements for both beam paths, using the 3D translation stage, power meter and varying the energy levels as needed. Ensure a systematic approach to data collection. Analyze your results critically, drawing conclusions based on the data obtained.

Safety Note: Do not place the power meter directly behind the focal point of the lens to avoid damage and ensure accurate readings. Be aware of the risk of injury at focal points.