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Optics Tutorials for the Quantum Photo-Science Laboratory at NAIST

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Lesson flow

These five lessons are a rapid introduction to the fundamental optics and equipment used in an optics laboratory. Each lesson is to be completed in about one week. Students are encouraged to work together to solve problems and build setups from scratch. It is very important that the instructor let the students struggle with the problems on their own and not give answers right away.

Just as in sports or music, drills are used to reinforce fundamental skills. Think shooting basketball free throws or playing scales on the piano. In optics, the fundamental skill is **laser alignment**. It starts easy with a small red laser, a couple of mirrors, a couple of irises, and a target. Lessons progress to include more complex optical components, including nonlinear crystals. The ultimate goal is to be able to understand and work with pulsed lasers. The nonlinear aspect of pulsed lasers opens up totally new phenomena with different optical components. This hardest tutorial has students find the laser pulse width using cross correlation via second harmonic generation (SHG) using a nonlinear crystal. The instructor should discuss nonlinear theory.

The linear spectroscopy tutorial is experimentally simple, but introduces data analysis and fitting techniqes using data collected with an FTIR. Here, the instructor provides a set of clear liquid samples. The students do not know what the molecules are (but are labeled with numbers), and students must use a Fabry-Pérot etalon to calculate the material refractive index of the samples to determine what molecule they have.

For larger groups students may be separated into separate tracks, where one group does the pulsed laser tutorial first and linear spectroscopy second, while the other group does these tutorials in reverse order. Lesson 1 must be done for everyone before moving on. An introduction to data analysis should be done in conjunction with the pulsed laser and FTIR tutorials.

The data analysis portion of these tutorials are in a separate GitHub repository.

Lesson 1: Basic Optical Elements and Beam Alignment

Goals

1. Learn basic optics components (laser, mirrors, irises, posts, etc.)
2. Basic mirror alignment using a red guide beam, two mirrors, and two irises

Mirrors

- Beam should hit close to the center (so there is room for adjustment later)
- Do not touch the mirrors (a laser can burn organic molecules, which can damage the mirror or mirror coating)
- Do not blow on the optics
- Handle the mirrors using a mirror mount as much as possible (not with your hands)

Mirror holders

- Use knobs to make tiny adjustments in x and y

Irises

- Irises help align beam in correct direction at correct height
- Once you align the beam, don't touch the iris
- Irises also block scattered light
- Use a collar or the post lock (on some ThorLabs post holders) in the post holder to fix the iris height.

Photodetector

- Converts photons into current (semiconductor based)

Where the lab's optical components are stored

- metric vs English units

Alignment — practice

- Put Mirror 1 close to the laser to limit beam divergence.
- Put Mirror 1 and Mirror 2 close together so we have maximum range of motion for the beam.
- Make the irises as far apart as possible for easier and more precise alignment

Aligning higher powered beams

The same mirror adjustments can be used to align Class 3 and 4 lasers, but please always follow the guidance from your facility's laser safety officer when using high-power lasers. In many cases, the recommendation is to use low powers for safer handling and to preserve the lifetime of IR cards while aligning free-space and unenclosed laser beams. However, it is important to note that, when the alignment is performed at reduced laser power, the alignment might need to be tweaked once full laser power is applied.

Irises are another special concern while working with high-powered lasers. We used black-plated iris blades (leaves) in the video since our laser power was relatively low. This coating will discolor, and the leaves can deform when higher laser powers are absorbed over long periods. We typically use stainless steel leaves when using higher power lasers to reduce the amount of light that gets absorbed. However, bare stainless steel iris leaves are typically more reflective than the black-plated leaves. When placing irises or any other component in the path, it is also important to check for stray reflections.

Operate the lasers at low powers for safer handling while aligning free-space and unenclosed laser beams. In our videos we have kept our laser power <2 mW by either limiting the laser drive current or including polarizing components in the setup prior to filming. Other ways to limit laser power can include operating a pulsed lasers in CW mode or limiting the pulse repletion rate. If the laser power cannot be reduced, a separate, lower-power laser is often used to perform the initial alignment. When using this approach, the beam from the alignment laser should enter the setup as close as possible to the same position and same angular orientation as the beam from the primary laser. But with both approaches (lowering the laser power or using a secondary aiming laser), the alignment will likely need to be tweaked once full laser power is applied. Please always follow the guidance from your facility's laser safety officer when using high power lasers.

Lesson 2: Using an oscilloscope

Functions of an oscilloscope

Graphs a waveform of voltage changing in time. (Voltage axis & time axis)

(A multimeter cannot measure time-dependence)

Voltage measurements (vertical)

- Voltage peak
- Peak-to-peak
- RMS voltage

Time & frequency measurements (horizontal)

- Period
- Pulse width

Many functions to measure a waveform

Three systems (adjustments)

1. Vertical: adjust attenuation or amplification of the signal. (Volts / division)
2. Horizontal: adjust the time base (time / division)
3. Trigger: stabilize a repeating signal or trigger a single event

Vertical controls

- **Position**: move waveform up and down on the screen. Volts-per-division changes waveform size and vertical step divisions on the screen.
- **Coupling**: DC, AC, ground. How to connect an electrical signal between circuits. Input coupling is the connection from the circuit to the oscilloscope.
  - DC coupling: shows all of the input signal
  - AC coupling: blocks the DC component so the waveform is centered around zero volts (useful if alternating current + direct current is too large for volts/div setting.
  - Ground: disconnects input signal from the vertical system. You can see where zero volts is on the screen.
    - Grounded input coupling & auto trigger mode — horizontal line on the screen represents zero volts. Switch from DC to ground and back -> can measure signal voltage level wrt to ground.
- **Bandwidth**
  - Bandwidth limit: limiting the bandwidth reduces the noise on the displayed waveform (can also reduce high frequency portion of the signal)
- Termination
- Offset
- Invert
- Scale

Horizontal controls

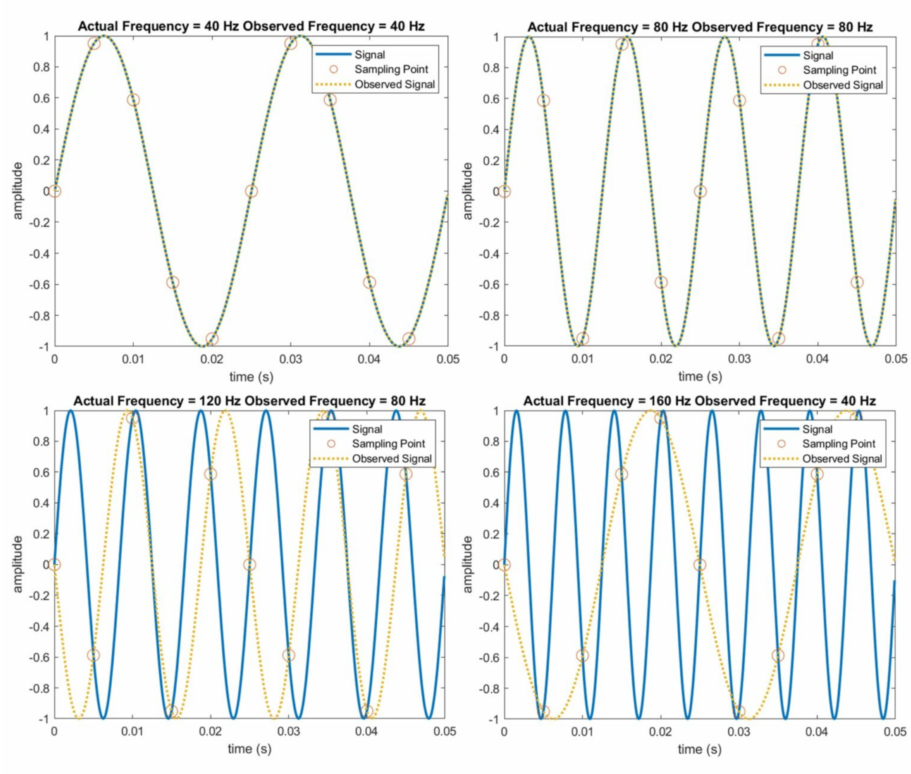
- **Acquisition**
- **Sampling**: converting part of an input signal into discrete electrical values.
  - A low sample rate compared to the input wave frequency may degrade or distort the sampled signal. In fact, the minimum sampling frequency must be > 2x the maximum frequency component of the signal to avoid artifacts (Nyquist-Shannon sampling theorem).
- **Position**: similar to vertical position, but for the time domain. Scale the horizontal divisions with sec/div setting.

- **Trigger position**: the trigger function synchronizes the horizontal sweep at the correct point of the signal for a clear display of the signal.
  - Stabilize repeating waveforms and capture single-shot waveforms.
  - Repetitive waveforms are displayed as static. A poorly triggered signal will result in the sweep starting at different places in the signal.

Oscilloscope Systems and Control

Sampling Theorem

Nyquist-Shannon sampling theorem



Lesson 3: Intro to pulsed laser alignment and nonlinear optics

Use the 800 nm pulsed laser tutorial setup

Review and introduction to new optical components

Quiz on basic optics components from last week.

New optics

- Retroreflector
- Translation stage
- Lens tube / beam path cover
- Focusing lens and mirror
- Nonlinear crystal
  - Nonlinear susceptibility
  - Properties of Beta Barium Borate
    * high damage threshold
    * Band edges at 0.19 - 3.3 um
    * Useful range 0.21 - 2.1 um
    * Efficient for SHG
    * Narrow angular acceptance bandwidth
  - Second harmonic generation
    * Depends on second-order susceptibility and square of the electric field

New instruments

- Camera (sensor and lens module)
- Photomultiplier
- Function generator
- Oscilloscope
- DAQ

Part A

Build an experiment to measure the beam pulse width. This may take a couple of days. Work in pairs or individually.

1. Use the beam splitter to split the incoming beam before the retroreflector so that one beam is reflected at 90° and is reflected off of two more mirrors before going through the second iris and hitting the curved mirror.
2. The transmitted beam will hit the retroreflector and get reflected to a lower height, hitting the square mirror and finally reflects off of the curved mirror.
3. Adjust the setup so that the two beams cross at about 25 cm from the curved mirror. This is about the focal point of the mirror.

Part B

Create an SHG signal from both beams, and then spatially and temporally overlap the beams to generate a third SHG beam. Work individually. Each person should be able to create the SHG beam.

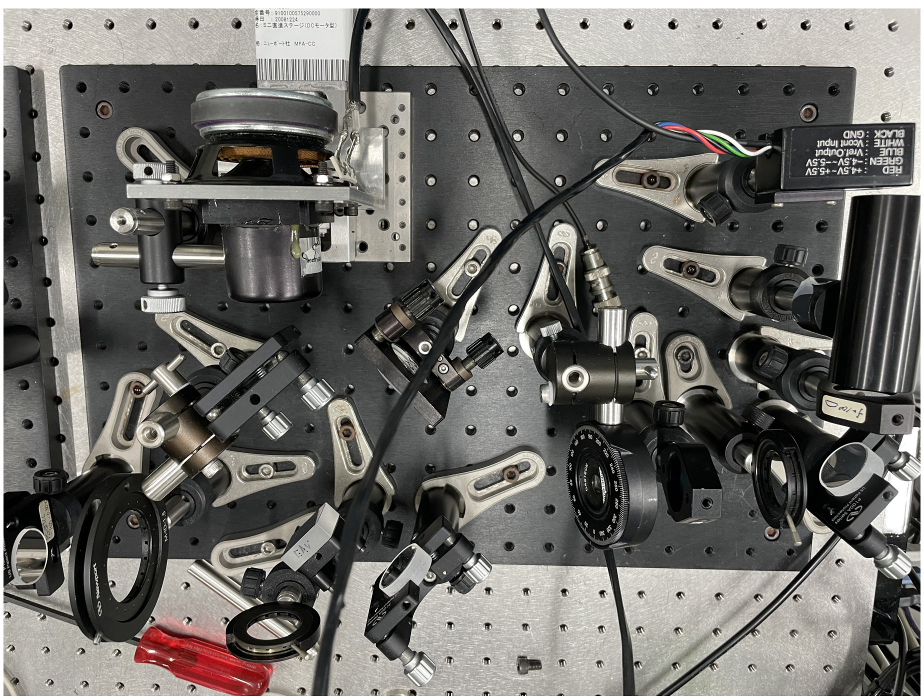
1. Use the camera to overlap the beams in the BBO crystal.

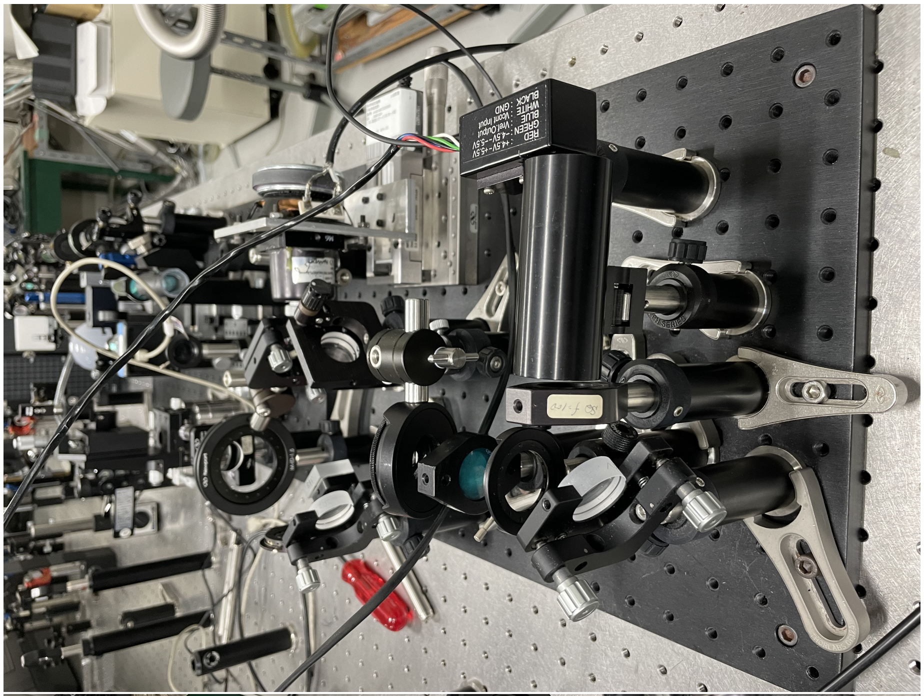
2. Adjust the angle of the BBO crystal so that the two exiting beams are about equal in brightness.
3. Use the translation stage to adjust the retroreflector position, adjusting the temporal overlap of the two beams. Watch for a third SHG beam to appear between the original two.
4. Adjust the mirrors so the middle SHG beam goes into the photomultiplier.(Make sure the photomultiplier is at the focal distance of the lens.)

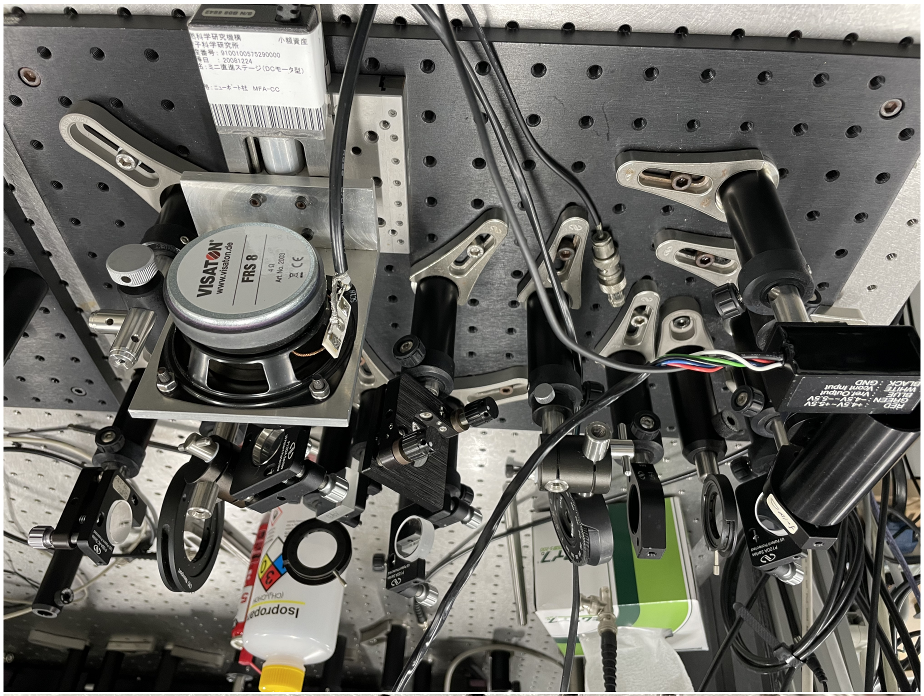
Part C

Each person collects their own data.

1. Measure characteristics of the femtosecond pulse on the oscilloscope by oscillating the retroreflector at 5 Hz with a function generator. (The retroreflector is mounted on a speaker.) Go to Lesson 3 to learn about oscilloscopes.
2. Use the piezo stage to adjust the temporal delay between the two beams and capture the signal strength in the LabView program.
3. Fit the data to a Gaussian curve to find the pulse width. Curve fitting is covered in a lesson on analysis and lab software.




RED : +4.5V~+5.5V
GREEN : -4.5V~-5.5V
BLUE : Vout Output
WHITE : Vext Input
BLACK : GND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Lesson 5: Find the Pump-Probe Overlap in a MIR Optics Setup

Goals:

1. Learn how to align an invisible beam
2. New optical components for MIR beams
3. Learn about transient spectroscopy
4. Spatially and temporally overlap two MIR beams (pump and probe)

Students will use the MIR optics table to overlap the pump and probe beams first through a pinhole and then through a thin sheet of germanium crystal, observing the nonlinear signal. If the student will be doing MIR pump-probe experiments, a sample with a shorter lifetime should also be used to observe the molecular dynamics and kinetics to understand nonlinear properties of molecules (such as anharmonicity).

New optics

- Difference Frequency Generation (DFG) crystal
- MIR filters, waveplates, polarizers
- Mechanical chopper
- Delay stage

New instruments

- Spectrometer
    - MCT detector
    - Grating
- Thermal power meter

Alignment steps

1. Generate and maximize the MIR beam
2. Align the path using the red diode laser and pinhole
3. Align the MIR pump and probe beams through the pinhole
4. Use the germanium crystal to find and maximize the nonlinaer signal with the spectrometer

Lesson 4: Etalon fringes and FTIR

Goals:

1. Use new equipment
2. Make an etalon
3. Measure the distance between two mirrors
4. Measure the refractive index of a material inserted between the mirrors

5. Measure the Rabi splitting in a neat liquid and in a diluted liquid

Part A: Fabricate mirrors (may not be necessary, depending on instrument availability)

1. Explain how to use the Au-sputter machine and each person makes a set of mirrors.
2. Explain where to store experiment samples and parts.
3. Explain the basics of the FTIR spectrometer and the software.

Part B: Measure fringes

1. Use spacers of three different thicknesses to demonstrate cavity fringes.
2. Calculate the cavity spacing from the fringe spacing.
3. Give each person a different solvent without telling them what they have. Have them try to figure out which solvent they have.
    1. Water: 1.333
    2. Isopropanol: 1.377
    3. Toluene: 1.497

Use peak-finding software.

Part C: Measure Rabi splitting

1. Use DPPA to measure Rabi splitting
    1. Neat
    2. Diluted in toluene

Fit with a double-Lorentzian function

Questions

Why is the cavity length different than the spacer thickness? What do you think contributes to the real cavity length? Why do you think the refractive index is different from the actual value? What are the sources of error? What are the cavity modes, physically? Why does the spacing change with cavity length or refractive index?

error: take apart cavity and put it back together.