Contents

Optics Tutorials for the Quantum Photo-Science Laboratory at NAIST

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Introduction

The documents here are for the instructor. 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.

There are essentially two tracks: using a self-contained spectrometer (FTIR) and an open optics setup. If there are enough students, you can make two groups and put them on different tracks and then switch.

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, and a couple of irises. 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 techniques 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. An introduction to data analysis should be done in conjunction with the pulsed laser and FTIR tutorials.

Data analysis and programming in Julia

The data analysis portion of these tutorials are in a separate GitHub repository and are to be given to students when they begin analysis.

After students complete an experiment lesson, they will analyze their results using Julia. It is important not only for students to develop skills in data analysis, but also to learn basic programming skills. This includes of course the basics like loops, conditionals, functions, etc. This also includes good pragramming practices and using standard practices for the language, Julia in this case. Make sure you review the Julia manual to make sure that you are familiar with best practices and ask questions on the Julia Discourse forum if you are unsure of something. The Julia community (as are many open source programming communities, generally) is friendly and open to newcomers.

The reason for emphasizing good programming skills is that most of the students will be doing data analysis in some language or another. If they do not learn the basics in the beginning, it will take a long time for them to do any analysis (I have seen some students take weeks just to do basic curve fitting). Also, if proper coding practices are not learned, then their analysis will be difficult for them to understand months later. Worse, future students won't be able to understand what they did at all! Finally, most students will not become professional scientists, but they will likely use data analysis in their future careers. Learning good programming practices will help them whereever they end up.

The reason I choose Julia is because is is a high-level language that is easy to learn and has a lot of built-in functions for data analysis. It is better than Matlab because it is free and open source, and it is also much faster. I prefer Julia to Python because it is faster and has a more consistent syntax. The plotting libraries are also much more intuitive and straightforward. They are also quite powerful and you can easily make interactive figures.

After they learn Julia, it really does not matter to me what language students use after that. Python is a great language and is used in many industries. Julia's syntax is quite similar to Matlab and Python, so it is easy to switch to those languages if needed.

Lesson 1: Basic Optical Elements and Beam Alignment

Goals

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

The Basics

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 small 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

Laser Safety (basics)

- Do not look directly into the laser beam
- Do not look at the beam reflection from a mirror
- Do not point the laser at someone else
- Use a laser card when aligning
- Do not bend down to the beam height; always work above the beam height

First steps

The first lesson is just practicing aligning using two mirrors and two irises. Explain the basics of the optics and the laser safety rules. Then demonstrate how to align the beam using the red laser. Ask them to try aligning the beam in different ways. What happens if the irises are close together? What happens if the mirrors are far from the laser source? What if the mirrors cannot be adjusted to go through both irises? Let students *play* with the optics (keeping safety in mind) so they get a feel for how they work.

Lesson 2: Using an oscilloscope

This lesson should be completed before measuring the SHG signal in the non-linear optics lesson. Make sure to give students the resources linked below so they can learn on their own.

Goals

1. Understand the basic functions of an oscilloscope
2. Learn how to measure voltage and time using an oscilloscope
3. Learn how to trigger a signal on 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

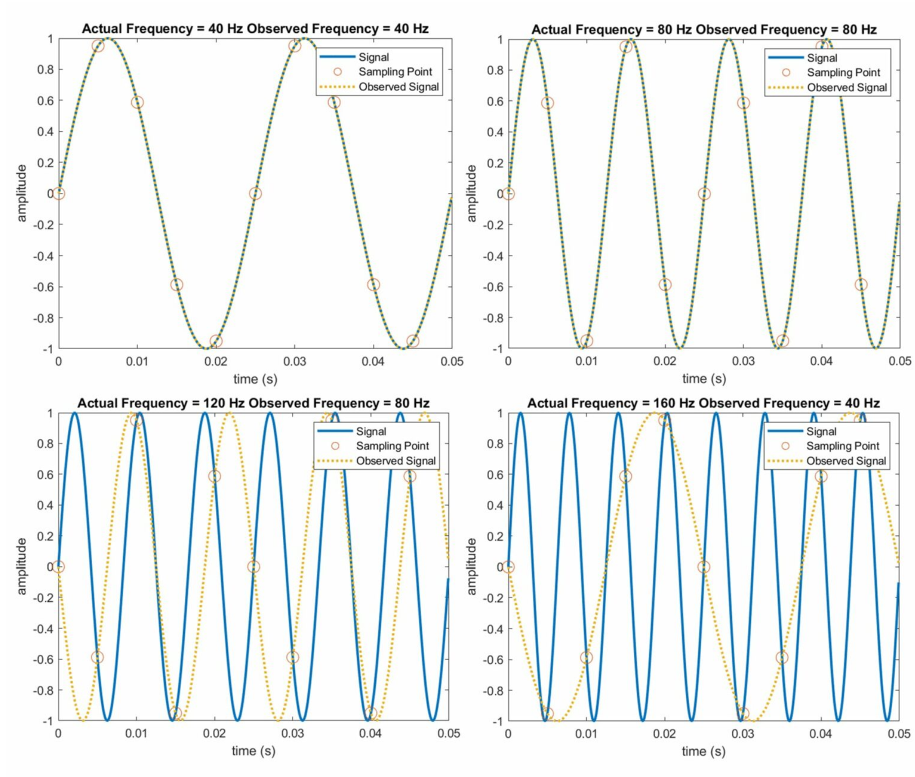
Horizontal controls

- **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 non-linear optics

Use the 800 nm pulsed laser tutorial setup to introduce students to the new optical components and instruments.

Goals

1. Review basic optical components
2. Use new optical components
3. Learn nonlinear optics concepts
4. Measure the pulse width of a femtosecond laser via autocorrelation

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 μm
    * Useful range 0.21 - 2.1 μm
    * 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.

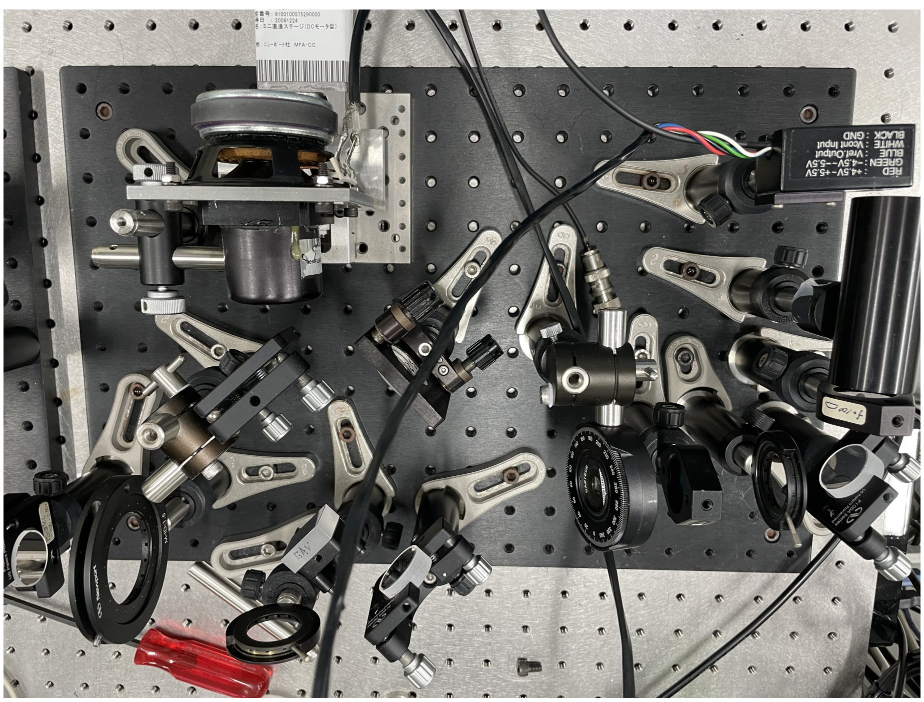
1. Use the camera to overlap the beams in the BBO crystal.

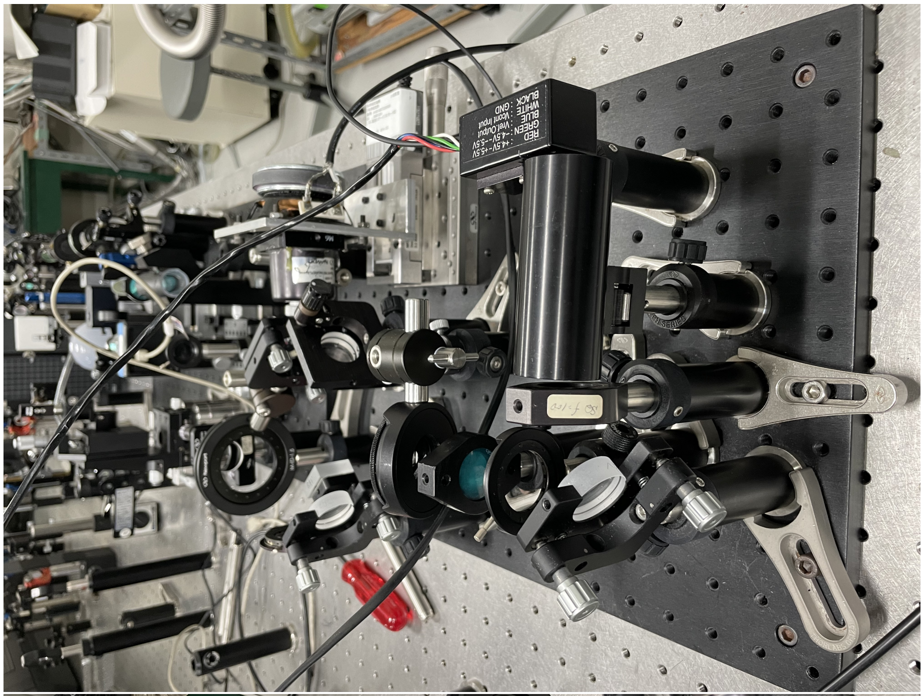
2. Adjust the angle of the BBO crystal so that the two exiting beams are about equal in brightness.
3. Use the translation stage to adjust the retroreflector position, adjusting the temporal overlap of the two beams. Watch for a third SHG beam to appear between the original two.
4. Adjust the mirrors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

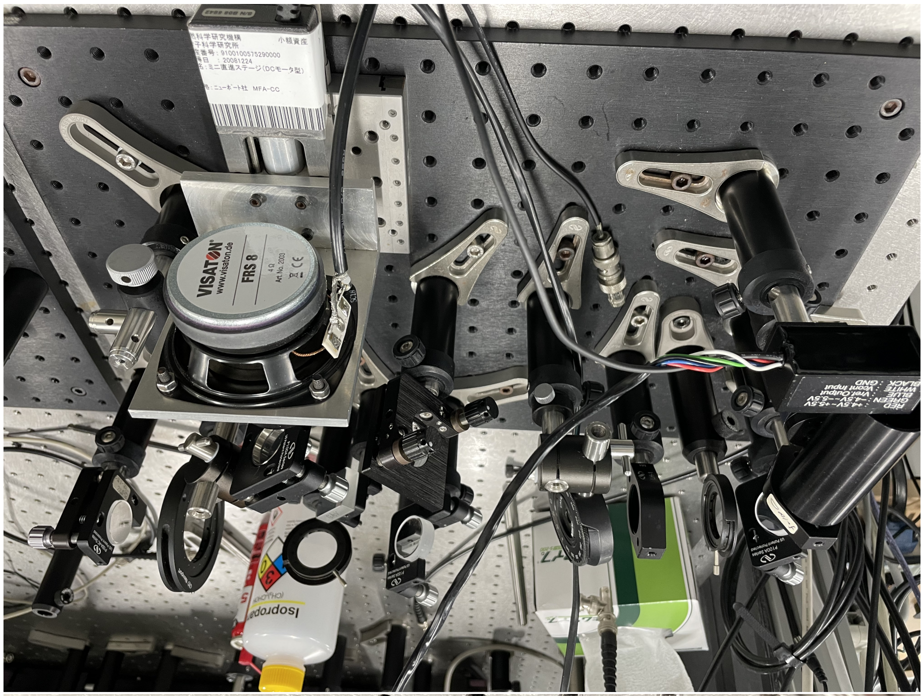
Part C

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 : Vref.Output
WHITE : Vcont 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 and instruments

- Difference Frequency Generation (DFG) crystal
- MIR filters, waveplates, polarizers
- Mechanical chopper
- Delay stage
- Pinhole
- 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 (can be done with the chopper on or off)

Lesson 5: Etalon fringes and FTIR

Goals

1. Learn how to use an FTIR, including the basic functions and how to measure a spectrum
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: 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 B: Measure Rabi splitting

1. Use an IR-active liquid sample to measure Rabi splitting
    1. Neat
    2. Diluted
2. Fit with a double-Lorentzian function

Questions

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

error: take apart cavity and put it back together.

A list of excellent video tutorials on the web

Thorlabs

- Mounting Your Optomech: Bases, Post Holders, and Posts
- How to align a laser
- Distinguish the Fast and Slow Axes of a Quarter-Wave Plate
- Build a Polarimeter to Find Stokes Values, Polarization State
- Use Laser Speckle to Find the Beam Focus
- Align an Off-Axis Parabolic (OAP) Mirror to Collimate a Beam
- Align a Linear Polarizer's Axis to be Vertical or Horizontal to the Table
- Align a Linear Polarizer 45° to the Plane of Incidence