Contents

Optics Tutorials for the Quantum Photo-Science Laboratory

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 it 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.

Timeline

Split into two groups. Everyone can do Part A together, but then split up the groups in Part B. Half will do FTIR spectroscopy first, the other half will start with nonlinear optics.

Part A

Basic optics (1 week) Intro to programming and data analysis (2 weeks)

Part B

FTIR spectroscopy (2 weeks)

Nonlinear optics (2 weeks)

Part C

Project-specific experiments (2 weeks)

Lesson 1: Basic Optical Elements and Beam Alignment

Lesson 1 introduces students to basic optical elements and alignment techniques. It is divided into two parts. The first part covers basic optical elements, alignment, and safety. The second part is an experiment to measure the pit width of a CD and DVD.

Remember that tutorials are not lectures but interactive sessions where students are encouraged to ask questions and participate in the discussion. They are also encouraged to handle the optical elements and align the beam themselves.

Part 1: Introduction to Optical Elements and Alignment

Goals

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

Flow

This tutorial is to be completed in five days. Results are presented the following week.

- Day 1: Basic optial elements, laser safety, and practice basic alignment
- Day 2: Review, assign optical disk pit width experiment
- Days 3-4: Optical disk pit width experiment
- Day 5: Review progress

The first lesson is laser safety and practicing alignment using two mirrors and two irises. Next demonstrate how to align the beam using the red diode laser. Ask students to try aligning the beam in different ways. Make it interactive by having them handle the optics and regularly asking questions to check understanding. Let students *play* with the optics (keeping safety in mind) so they get a feel for how they work.

Alignment tips

- 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.
- Bending the path at 90° makes it easier to follow the beam path.

Questions to ask students

- What happens if the irises are close together? (try it!)
- What happens if the mirrors are far from the laser source?
- What if the mirrors cannot be adjusted to go through both irises?
- What do you need to align the beam along a straight path?

Laser Safety (basics)

Cover the basics of laser safety first. Students will take a full laser safety course from the university, but here we emphasize the basics:

- Remove jewelry and reflective objects
- Do not look directly into the laser beam

- Do not look at the beam reflection from a mirror or other reflective surfaces
- 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
- Block the beam before making adjustments to the optics
- Block the beam first if you have to pick something off of the floor or work near beam height
- Always be aware of where the beam is going
- The laser operator is responsible for the safety of everyone in the room
- The beam should be parallel to the table surface

Demonstrate the laser card and how to use it to find the beam. Also demonstrate how improper beam blocking can lead to the beam escaping the table and potentially endangering others.

Optical elements

The following optical elements should be introduced:

- Mirror
- Mirror mount
- Post
- Post holder
- Base plate
- Fork
- Diode laser

Be sure to explain the purpose of each element and how they are used in an optical setup, as well as safety precautions. When explaining, let students handle and assemble the components. For example, have them assemble a post holder with a post and a mirror mount.

Cover the following details for each element:

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)
- Direct handling of mirrors should be done with gloves

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) on the post holder to fix the iris height.

Part 2: Optical disk pit width experiment (CD and DVD)

Goals

- Apply alignment techniques learned previously
- Have them find accurate theoretical values for the pit width
- Properly present results

Flow

1. Review the alignment procedure
2. Explain principles of how a CD/DVD works
3. Have students measure the pit width of a CD and DVD
4. Have students calculate the pit width using the formula for the diffraction limit
5. Have students present their results

Review

- What is the purpose of the irises?
- What safety precautions must you take when working with a laser?
- What should you do if you need to pick something up off the floor while working with a laser?
- How do you make fine adjustments to the beam path?
- We have a red and green laser. What are their wavelengths? (633 nm, 533 nm)

Experiment description

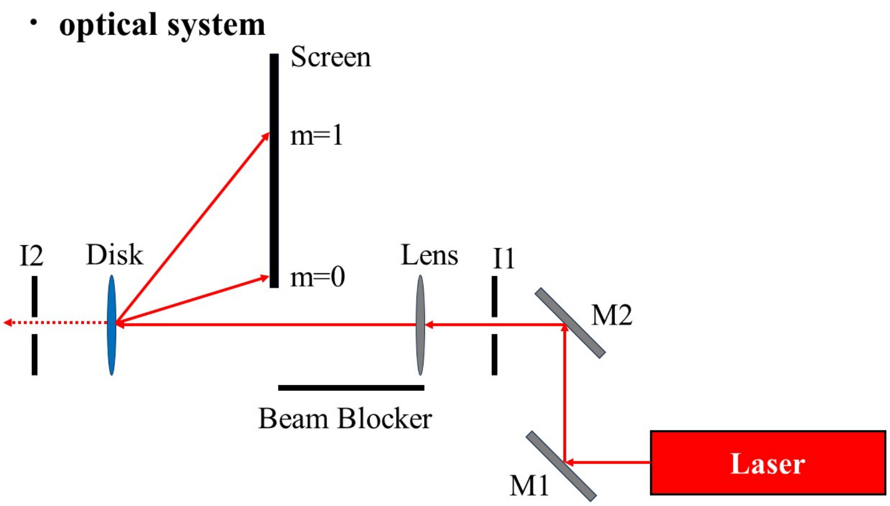
Write a schematic of the optical setup on the board. List the components used in the experiment. They must describe the setup in their presentation. When helping the students, drop hints to help them figure out the setup and understand sources of experimental error.

Questions to ask students

- How does the pit width change with the wavelength of the laser?
- How does reading a CD or DVD work?
- When the beam hits a pit, what happens?

- When then laser beam hits a pit that is a half wavelength deep, what happens?

Arrange the experiment setup before the students arrive:



Presentation requirements

- Purpose
- Principles of the experiment and procedure
- Schematic of the setup
- A picture of diffracted light hitting the screen
- Optical elements and their description
- Results
- Error analysis and sources of error (compare to literature values with references)
- Considerations for improving accuracy

Reflection grating formula

The formula for the pit width is derived from the reflection grating formula: $$m\lambda = d(\sin\theta_{i}-\sin\theta_{0})$$

where m is the order of the diffraction, λ is the wavelength of the laser, d is the pit width, θ_{i} is the angle of the ith order diffraction, and θ_{0} is the angle of the zeroth order diffraction. Angles θ_{i} and θ_{0} are related to the x and y coordinates of the beam:

$$\sin\theta_{i}=\frac{x^2}{\sqrt{x^2+y_{i}^2}}$$

$$\sin\theta_{0}=\frac{x^2}{\sqrt{x^2+y_{0}^2}}$$

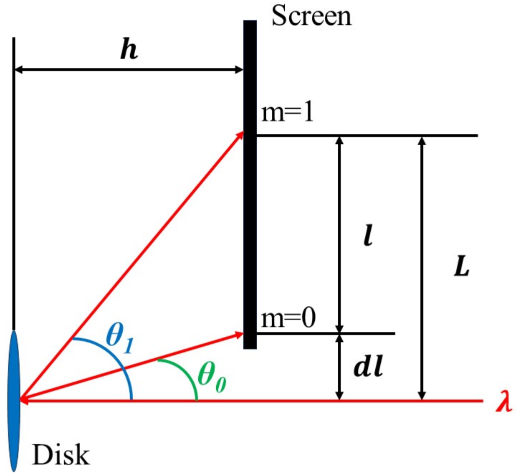
Assume $\theta_0 \approx 0$ for this tutorial.

Notes

- CD pit width: 1.6 µm
- DVD pit width: 0.74 µm
- Literature values may differ slightly

- **Track Pitch**

$$d = \frac{\lambda}{\sin\theta_1 - \sin\theta_0}$$
$$= \frac{\lambda}{\frac{L}{\sqrt{L^2+h^2}} - \frac{dl}{\sqrt{dl^2+h^2}}}$$



Lesson 2: Introduction to Programming and Data Analysis

See the separate GitHub repository for the programming tutorial.

Lesson 3: Fourier-Transform Infrared Spectroscopy and Fabry-Pérot Cavities

This lesson introduces students to molecular vibrations, Fabry-Pérot cavities, and the basics of Fourier-transform infrared spectroscopy (FTIR). The lesson is divided into three parts. The first part covers Fabry-Pérot cavities and molecular vibrations. The second part is an experiment to measure the refractive index of two unknown molecules using the FTIR. The third part is a programming tutorial to analyze the experimental data and plot the results.

Part 1: Steady-State Molecular Spectroscopy

Goals

- Briefly introduce the basics of molecular vibrations.
- Learn the fundamentals of how an FTIR spectrometer collects information about molecular vibrations.
- Learn what a Fabry-Pérot cavity is and how to interpret the data it produces.

Flow

Give the following introduction with the FTIR spectrometer and prepare molecular and cavity examples to demonstrate the concepts.

Give a very brief introduction to molecular vibrations, particularly molecular absorption and emssion. Introduce the idea that vibrational modes can be excited by infrared light and that the FTIR spectrometer can measure these modes. The combination of vibrational modes in a molecule are unique to that molecule, and the FTIR can be used to identify unknown molecules. Thus, the mid-infrared region is often called the ”fingerprint region”.

Next introduce the FTIR spectrometer and how it works. Explain that the FTIR uses a Michelson interferometer to measure the intensity of light as a function of wavenumber. The FTIR can be used to measure the transmittance or absorbance of a sample. The transmittance is the ratio of the intensity of the transmitted light to the intensity of the incident light. The absorbance is the logarithm of the reciprocal of the transmittance. Here explain the Beer-Lambert law, which relates the absorbance to the concentration of the absorbing species. Demonstrate this with two samples of different concentrations or two samples of different molecular species to show the different spectra.

Finally, introduce the Fabry-Pérot cavity. Explain that the Fabry-Pérot cavity is a resonant cavity that can be used to enhance the intensity of light at certain wavenumbers. The Fabry-Pérot cavity is made of two mirrors separated by a spacer. The cavity modes are the standing waves that can exist in the cavity. The cavity modes are determined by the cavity length and the refractive index of the intracavity material. Feel free to use simulations, such as the Transfer Matrix Method, to demonstrate how the cavity modes change with cavity length and refractive index. Here is an online simulation demonstrating the electric field. Here, prepare a gold cavity to demonstrate the cavity modes with the FTIR. A length-adjustable cavity can be used to demonstrate how the cavity modes change with cavity length.

Part 2: FTIR Experiment to Measure Refractive Index

Goals

- Measure the fringe spectra of two unknown molecules in cavities using the FTIR.
- Determine the refractive index of the molecules using the cavity mode spacing.

Setup

Prepare two molecules, such as methanol and toluene, and label them as sample 1 and sample 2.

- Methanol n = 1.3
- Toluene n = 1.5

First explain how to use the FTIR spectrometer. Then demonstrate how to construct a cell with a liquid sample and mirrors. Also show how to dissasemble the cell and clean it.

FTIR start up and measurement

1. Turn on the FTIR and let it warm up.
2. Take a background before a measurement. (explain how to choose the background)
3. Save the data.
4. Turn off the FTIR and close the software.

Part 3: Data Analysis and Plotting

Goals

- Load data from the FTIR experiment.
- Analyze the data to determine the refractive index of the two unknown molecules.

The analysis can be done by using either a maxima finding algorithm (easier) or a fitting algorithm (harder). Make sure the students use the file structure from the main programming tutorial for consistency. The analysis should be done independently by the students, but the instructor should be available to help.

Step 1: Loading data into a `DataFrame`

If you have ever used Python, you may be familiar with the popular `pandas` library. `DataFrames` is the Julia equivalent, and both are used to store and manipulate data in a table format. Once you load plain text data into a `DataFrame`, it is easy to perform analysis on sections or slices of the data. First use the `CSV` or

`DelimitedFiles` (for simple cases) packages to load the text file, then store it in a `DataFrame`.

Here is a simple `DataFrame` object:

```
data = DataFrame((a=[1, 2], b=[3, 4]))
```

Once the data is loaded, you can access columns in a few different ways. In this example, we can access column `a` using `data.a` or `data[!, :a]`. Find more on the `DataFrames` documentation page.

Load your cavity data into a `DataFrame` and plot it in Makie. Choose two neighboring peaks and find the cavity length by finding the difference between the two peaks. This can be done using the relation

$$\Delta\nu = \frac{1}{2nL}$$

where $\Delta\nu$ is the frequency difference between the two peaks, n is the refractive index of the material, and L is the cavity length.

Step 2: Finding the peak frequency

Finding the peak frequency by eye is fine for rough approximations, but ideally we want to fit the data to a model. What line shape does a cavity mode have? Explain your choice of fitting function. Look up a model for a molecular mode and write a Julia function based on it. Next, we need to select a range of data that includes only two peaks. We can do this in a few ways. Perhaps the simplest is to `filter()` the data based on a lower and upper bound. The `filter()` function is general, and not unique to the DataFrames package.

Here is an example of filtering a `DataFrame` by row value:

```
using DataFrames

df = DataFrame(x=1:10, y=sin.(1:10))

newdf = filter(row -> row.x > 10, df)
```

Since we want two bounds, we will need the boolean AND operator, `&&` (OR is `||`). Try this for yourself by modifying the example above.

Finally, plot your raw spectrum and two fits, one for each cavity mode.

Quiz Questions

- When Abs = 2, what is the ratio of the intensity of the incident light and transmitted light? (Ans: 1%)
- What are the sources of error?
- What can be done to reduce the error in the refractive index measurement?

- Why does the transmittance of cavity modes of the gold cavity increase with wavenumber?
- Why is the cavity length different than the nominal spacer thickness?
- What do you think contributes to the actual cavity length?
- What are the cavity modes, physically?
- Why does the spacing change with cavity length or refractive index?

Lesson 4: Introduction to Pulsed Laser Alignment and Nonlinear Optics

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

A handout for this lesson is in a separate document.

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.

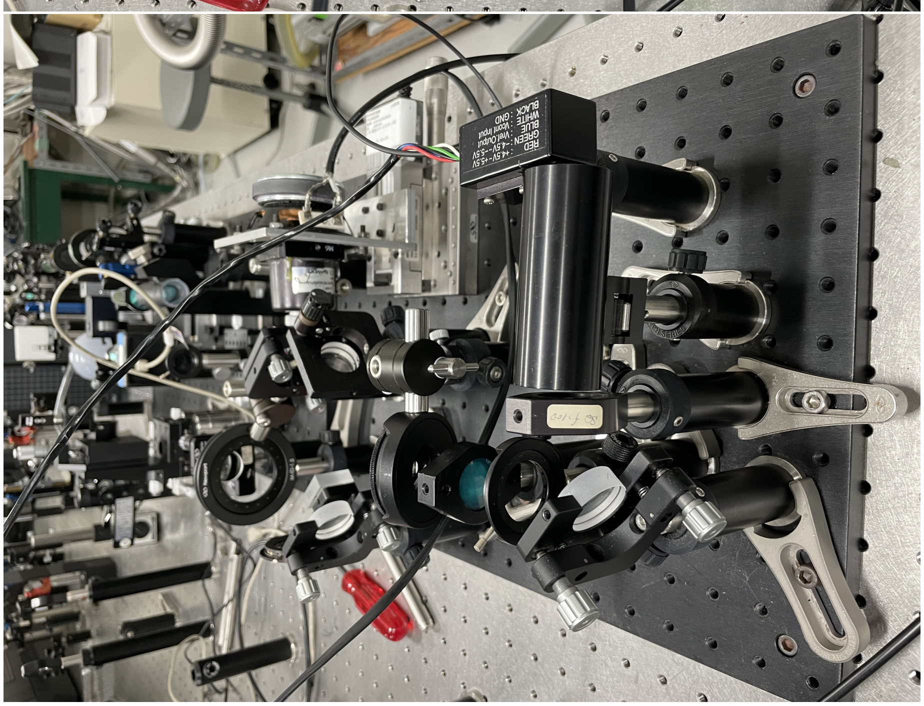
1. Use the camera to overlap the beams in the BBO crystal.
2. Adjust the angle of the BBO crystal so that the two exiting beams are about equal in brightness.
3. Use the translation stage to adjust the retroreflector position, adjusting the temporal overlap of the two beams. Watch for a third SHG beam 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.)

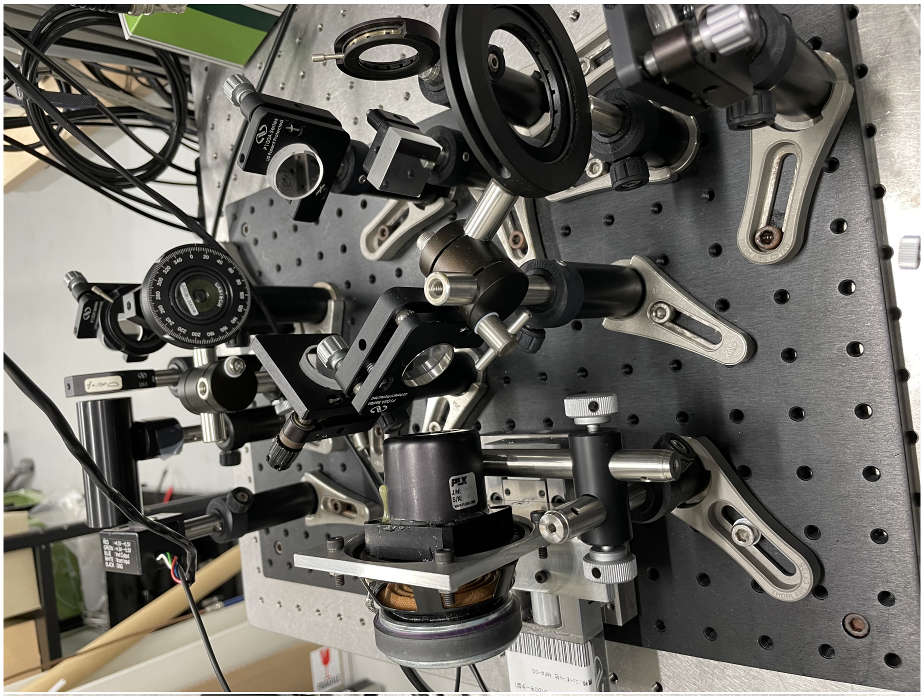
Part C

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.



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Lesson 4: Handout

1. Introduction

1.1 Nonlinear Optics

Nonlinear optics (□□□□□) investigates phenomena arising from changes in the optical characteristics of a material due to exposure to light, often from a laser. The term ”nonlinear” refers to the material's response to the applied laser's optical field. Specifically, this nonlinearity is characterized by how the material's polarization (□□), denoted as $\mathbf{P}(t)$, varies with the strength of the applied electric field (□□), represented as $\mathbf{E}(t)$. In our fundamental optics, we treated this generated polarization as a linear function of the electric field:

$$ \mathbf{\tilde{P}}(t) = \mathbf{P}^{(1)}(t) = \epsilon_0\chi^{(1)}\mathbf{E}(t),$$

where we called $\chi^{(1)}$ the linear optical susceptibility (□□) and ϵ_0 is the permittivity of free space. In general, however, polarization can be expressed as a power series of the applied electric field:

$$ \mathbf{P}(t) = \epsilon_0\chi^{(1)}\mathbf{E}(t) + \epsilon_0\chi^{(2)}\mathbf{E}^2(t) + \epsilon_0\chi^{(3)}\mathbf{E}^3(t) + ...,$$

where $\chi^{(2)}$ is called the second-order *nonlinear* optical susceptibility, $\chi^{(3)}$ is the third-order *nonlinear* optical susceptibility, and so on.

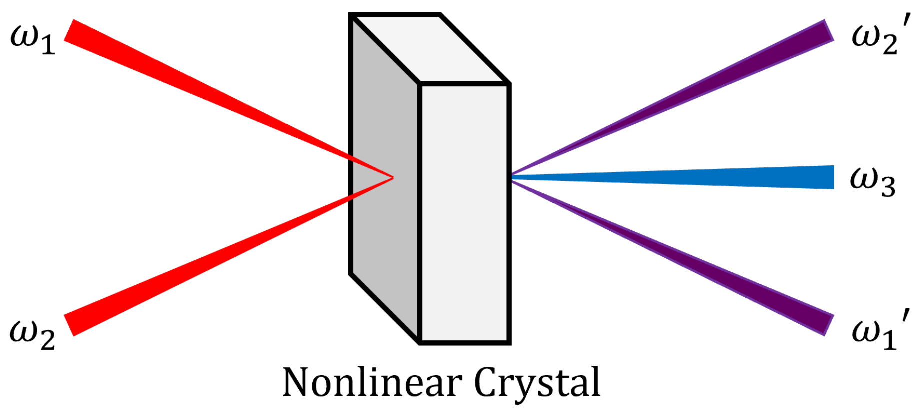
A material, typically a crystal, whose linear susceptibility ($\chi^{(1)}$) is much greater than the nonlinear optical susceptibilities ($\chi^{(2)}$, $\chi^{(3)}$, ...) is called a *linear crystal*. For a linear crystal, the polarization contributions of the higher, nonlinear terms can be neglected. Hence, the first equation is used for this case. An example of linear crystals are Calcite (CaCO3) and quartz (SiO2), which are both commonly used to demonstrate birefringence (□□□). On the other hand, there are crystals whose nonlinear optical susceptibilities are significant enough so that their polarization contributions can not be neglected. These type of crystals are called *nonlinear crystals* and they are utilized in a wide-range of optics experiments due to their capability to exhibit interesting optical effects.

1.2 Second-Order Nonlinear Polarization, $\mathbf{P}^{(2)}(t)$

Let us consider a nonlinear crystal whose second-order nonlinear optical susceptibility is much more significant than the other susceptibility (*i.e.*, $\chi ^{(2)} » \chi ^{(1)}, \chi ^{(3)}, ...$). The polarization that this crystal generates can be called as the second-order nonlinear polarization, which is given by:

$$ \mathbf{P}^{(2)}(t) = \epsilon_0\chi ^{(2)}\mathbf{E}^2(t).$$

To see what will happen if we use a second-order nonlinear crystal, let us consider a simple experimental setup shown in the given figure below.



Two beams at different frequencies (ω_1 *and* ω_2) *are incident to a nonlinear crystal. Under appropriate configuration, a third beam at a different frequency,* ω_3, *can be generated.*

Here, the two beams apply a total electric field strength of

$$ \mathbf{E}(t) = E_1e^{-i\omega_1 t} + E_1^*e^{i\omega_1 t} + E_2e^{-i\omega_2 t} + E_2^*e^{i\omega_2 t},$$

to the crystal. Using equation the above equation, the resulting second-order nonlinear polarization generated in the crystal can be written as

$$ \mathbf{P}^{(2)}(t) = P^{(2)}(0) + P^{(2)}(t) + \left[P^{(2)}(t)\right]^*.$$

The first term in the above equation is a polarization contribution at $\omega = 0$:

$$P^{(2)}(0) = 2\chi^{(2)}\left[E_1E_1^* + E_2E_2^* \right],$$

which leads to a process known as *optical rectification* in which a static electric field is created within the nonlinear crystal. On the other hand, the second term (the third term is just its complex conjugate) represents polarization contributions from the sum and difference of ω_1 and ω_2:

$$ P^{(2)}(t) = \chi^{(2)}\left[E_1^2e^{-i\left(2\omega_1\right) t} + E_2^2e^{-i\left(2\omega_2\right) t} + 2E_1E_2e^{-i\left(\omega_1+\omega_2\right) t} + 2E_1E^*_2e^{-i\left(\omega_1-\omega_2\right) t}\right].$$

These contributions are responsible for generating radiation at a different frequency. Specifically, the first two terms in the above equation correspond to the second-harmonic generation (SHG), where the generated radiation has a frequency of $2\omega_1$ or $2\omega_2$. The third term of the above equation corresponds to the sum-frequency generation (SFG), where the generated radiation has a frequency equal to the sum of ω_1 and ω_2. Then, the last term corresponds to the difference-frequency generation (DFG), where the generated radiation has a frequency equal to the difference of ω_1 and ω_2. Note that if one of the two beams is not present (which is equivalent to the case where ω_1 or $\omega_2 = 0$), we can still observe SHG (*why is that so?*).

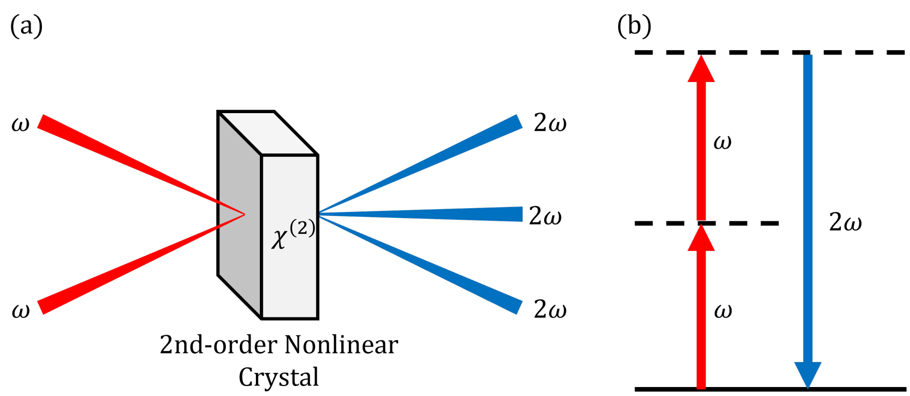
In ordinary experiments, the so-called *phase-matching* between the nonlinear crystal and the incident beams will also determine the characteristic of the outgoing beams. For example, if the *phase-matching condition* is not completely met, the outgoing beams may still have their original beam travelling in the same line with its own SHG beam (e.g., $\omega_1'=\omega_1, 2\omega_1$ and $\omega_2'=\omega_2, 2\omega_2$). Practically speaking, you can choose which components will be radiated by properly selecting the polarization of the incident beam and the orientation of the nonlinear crystal.

Reference: Chapters 1 & 2 of the Nonlinear Optics (2nd Ed.) by Robert W. Boyd

2. Practice Experiment: Second-Harmonic Generation via Sum-Frequency Generation

Overview and Objective

For this tutorial, the main goal is to introduce you to another set of optics and instruments, and use these to demonstrate one of the interesting phenomena in nonlinear optics—the second-harmonic generation (SHG) through Sum-Frequency Generation (SFG) (see Figure below)



A setup demonstrating Second-Harmonic Generation (SHG) via Sum-Frequency Generation (SFG): (a) geometry of the interaction assuming that the spatial, temporal, and phase-matching conditions are satisfied, and (b) its energy-level description.

You will use a single laser source to create two beams at equal frequency, $\omega_1 = \omega_2 = \omega$, then direct these beams to hit the same spot of a second-order nonlinear crystal. This will satisfy the *spatial overlap condition*. This condition will make sure that the two beams will interfere at the same point inside the crystal. Then, you will make sure that the two beams have the same optical path length. This will satisfy the *temporal overlap condition*. This second condition will make sure that the two beams are also in-phase when they interfere in the crystal. By satisfying these conditions, together with the phase-matching condition that you can meet by adjusting the orientation of the crystal, you can generate a third beam at the second-harmonic frequency, 2ω. In terms of wavelength, the SHG beam will have a wavelength half the incident beam's wavelength, *i.e.* $\lambda/2$. Therefore, your SHG beams will have a different color from your laser source.

Optics and Instruments

- Laser source ((a) a guide beam will be used in the start as you build and align your setup; (b) the actual pulsed laser will be used after when your setup is ready for testing)

- mirrors
- irises
- beam splitter
- retroreflector
- optical filter
- translation stage
- lens tube with a beam path cover
- Beta Barium Borate (BBO) nonlinear rystal
- photomultiplier
- camera (sensor and lens module)
- oscilloscope
- data acquisition (DAQ) instrument.

Procedures

IMPORTANT: The following optics are fixed in the optical breadboard and will serve as your starting setup:

1. the first iris, where the guide beam and the actual pulsed laser will pass through
2. the retroreflector, which is mounted on a speaker and is on top of a translation stage
3. the second iris
4. the curved mirror.

In addition, the height of these optics are already optimized to the height of the actual pulsed laser so it is recommended not to adjust their heights unless, for some reason, they really needed to be adjusted.

Part A - Satisfy the Spatial Overlap Condition

1. Use a beam splitter to split the incoming beam. Place it in between the first iris and the reftroflector so that one beam is transmitted straight to the retroreflector and the other beam is reflected 90° with respect to the transmitted beam.
2. Using two mirrors, direct the reflected beam so that it will go through the second iris and hit the curved mirror.
3. Using the square mirror, direct the transmitted beam (which is reflected to a lower height by the retroreflector) so that it will also go through the second iris and hit the curved mirror.
4. Adjust the setup so that both beams are:

   a. traveling in a straight line as they hit the curved mirror. A preliminary check is to make sure that the two beams are vertically aligned on the surface of the curved mirror. Another way to check (a stricter one) is by removing the curved mirror and then check if the height of each beam is not changing significantly after several centimeters;

b. crossing (intersecting) at the focal point of the curved mirror, which is about 25cm from the surface of the curved mirror. You can use an iris to check if the two beams are overlapping at the focal point.

After doing the steps above, your setup is now ready to be tested using the actual pulsed laser. Depending on the situation, it may also mean that you need to relocate your setup to where the actual pulsed laser is going to enter.

5. Place the BBO crystal at the focal point.
6. Place a camera module, which is connected to a monitor, a few centimeters behind the BBO crystal. You may need to adjust the camera's position so that it is focused at the surface of the BBO crystal. Further optimize the overlap of the beams.

Conceptual Questions

- Given the same laser source, are there other nonlinear crystal that can be used in this SHG experiment?
- Why is it recommended that the two beams overlap at the focal point of the curved mirror? What will happen if you overlap the two beams away from the focal point?

Part B — Satisfy the Temporal Overlap Condition

1. Adjust the angles of the BBO crystal so that you will see two outgoing SHG beams having similar brightness.
2. Use the translation stage to adjust the retroreflector position. While adjusting, watch for another beam to appear between the original two SHG beams. This generated beam is your third SHG beam.

Conceptual Questions

- How is timing of each beam at the overlap relates to their respective optical path length?
- Why the third SHG beam appears in between the two SHG beam and not elsewhere?
- Assuming there is no loss of energy in the experiment, how the energy (or intensity) of the third SHG beam relates to the energy (intensity) of the two SHG beams?

Part C — Measure the Third SHG Beam

1. Place the optical filter after the BBO crystal so that only the third SHG beam will pass through.
2. Use a mirror to reflect the third SHG beam to a lens. A lens tube, whose length is roughly equal to the focal distance of the lens, is also attached to the lens to minimize unwanted light.
3. Place the photomultiplier at other end of the lens tube. You need to connect it to a power supply and to an oscilloscope to make sure that it is detecting the third SHG signal.
4. Connect the translation stage to a dedicated control system and use a dedicated LabView program to finally measure the third SHG beam signal.
5. Depending on the situation, you can also use a function generator and a DAQ instrument to assist you in measuring the third SHG signal.
6. Fit the data to a Gaussian curve to find the pulse width of your third SHG beam.

Conceptual Questions

- How can you verify that it is the third SHG beam that passed through the optical filter?
- The intensity of the detected signal changes as the translation stage moves during the measurement. Why is that so? What does it mean if the detected intensity is at its maximum/minimum?

Project 1: 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)

Appendix A: 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

Appendix B: 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

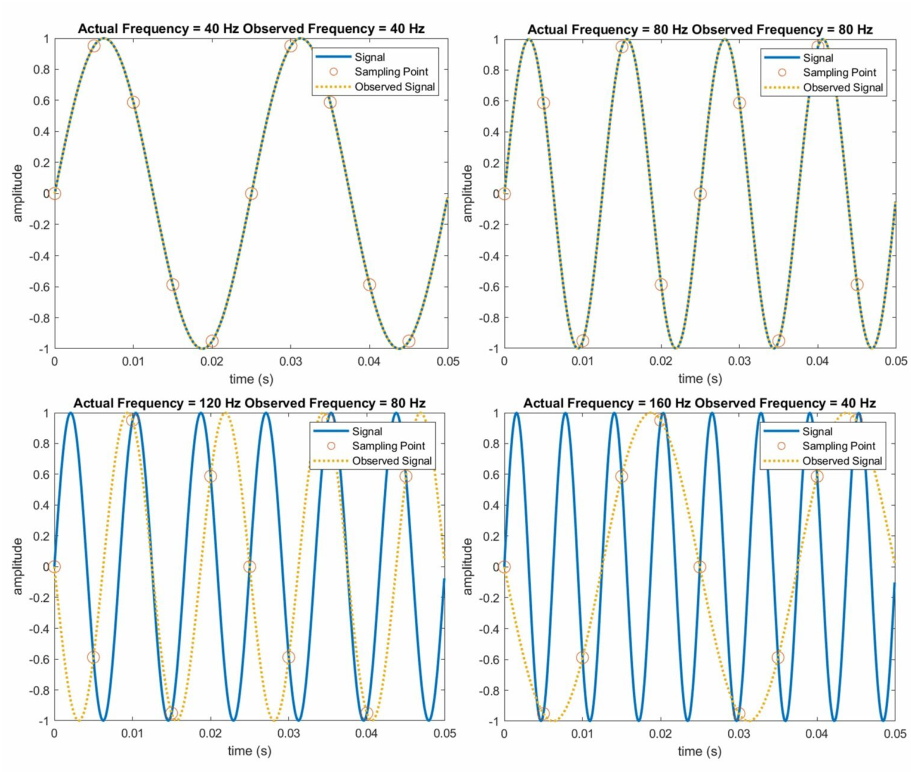
Horizontal controls

- **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



Actual Frequency = 40 Hz Observed Frequency = 40 Hz
Actual Frequency = 80 Hz Observed Frequency = 80 Hz
Actual Frequency = 120 Hz Observed Frequency = 80 Hz
Actual Frequency = 160 Hz Observed Frequency = 40 Hz
Signal
Sampling Point
Observed Signal
amplitude
time (s)