OPTIX Module 1 – Intermediate
Introduction to optics and optical elements

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1 Objectives:

In this module you will learn about

- the proper use and handling of *research-grade* optics equipment;
- how to use mirrors to align laser beams;
- various lenses and their applications;
- diffraction gratings and their use in spectrometers;
- polarization of light.

Use this manual as you work through the module to keep track of your notes and thoughts. In addition, you will have to add a few printouts or add additional sheets of paper containing data tables, sketches, or additional notes. You will *not* write a separate lab report after this module, because we want to give you enough time to thoroughly familiarize yourself and *play* with the equipment, but you will be graded on how well you complete this manual.

2 Tests and assessment:

In preparation for this module, read through the whole manual and answer the questions that are marked with a *. You should also watch the VIDEOs that are posted on our website (www.willamette.edu/cla/physics/info/NSF-OPTIX). They are meant to accompany this manual and will show you some critical steps of the module. When you come to lab, be prepared to discuss your answers to these questions with your classmates and your instructor.

You will also take a short test ("Laser Safety Test") before you begin working on this module to ensure that you have watched, read, and understood the *Laser Safety Material*.

Lastly, in order to assess the success of this module, you will take a short assessment test before you start ("pre-assessment"), and another one after you have successfully completed this module ("post-assessment"). At this point you will also have the opportunity to provide us with feedback about the module that we will use to improve it for the next student generation. Thank you for your support!

3 Equipment:

For this module you will need the following equipment. You can find everything that is specific to this module only in the box labeled 'Module 1 demos' that is located in one of the cabinets in the OPTIX lab. In addition, you will use equipment that is shared by several other modules; you can find it in the drawers and cabinets in the OPTIX lab (all of which are labeled). Lastly, equipment for the lasers is in the box labeled 'HeNe Laser'. Please feel free to ask your instructor for help. Note: All numbers are part numbers from Thorlabs.

- Optical cleaning tissue ('Optics Paper', MC-5), hemostats/forceps (FCP), isopropyl alcohol, compressor, DEMO 1 (flat mirror)
- HeNe laser (HNLS008L, R), lightbulb, piece of paper and detector card (VRC2), spectrometer (Mightex BD1), filter (FLHO5633-5)
- DEMO 2 (spherical mirror), glass slide, power meter (PM100A + S121C), DEMO 3 and 4 (mirrors with reflective and dielectric coating (BB1-E03))

- Several kinematic mirror mounts, mirrors, posts, post holders, table screws, dogs, two irises (ID8)
- DEMO 5 and 6 (converging and diverging lens, LA1509 + LC1120 or LA1131 + LC1715), DEMO7 (asphere, AL1225M), DEMO 8 (cylindrical lens), 20x beam expander (GBE20-A) or a 50 mm/1000 mm lens pair.
- DEMO 9 (optics with burned dielectric coating)
- DEMO 10a: 50 mm lens; DEMO 10b: 50 mm lens with water; DEMO 10c: 50 mm lens with immersion oil; DEMO 10d: 50 mm lens with immersion oil
- Several research-grade diverging and converging lenses, cylindrical lenses, aspheres, achromats, and lens mounts
- Tilt plate (glass slide), razor blade
- Prism pair
- OptoTune lens with variable focal length, a pair of +3.0 and a pair of -3.0 glasses
- DEMO 11 (Echelle diffraction grating), various research-grade transmission and reflection gratings
- White LED, battery
- Half- and quarter-waveplates with mounts (WPMH10M-633, WPMQ10M-633), polarizing beamsplitter cubes (PBS122), polarizers (LPVISE100-A)

4 Required background knowledge and things you need to do before starting this module:

This is the very first OPTIX module, so relax, you don't need to know much coming into this lab. A few basics will do, and this manual and the associated module will teach you most of them. **Make sure to read through the *whole* manual before coming into the OPTIX lab, and mark everything that you find difficult to understand.** Note that this module is longer and more text-heavy than the following modules since it is your first introduction to optics and we assume that you know pretty much nothing :).

During your lab time, you can work through parts of the manual with your lab group and instructor, and you will get a lot of hands-on experience. The main purpose of this very first module is to make sure that you are safe and that the equipment does not get damaged. You will learn how to handle research-grade optics equipment correctly, and how to protect yourself from laser radiation in particular. So for now, here are just a few pointers for **good general lab behavior**. Please initial each item to show that you have read *and understood* it. You can always ask your instructor if you have questions before initialing an item.

- This is a research lab, so leave your food and your drinks outside. A good place to store everything, especially if you are working as part of a large group, is the Physics Lounge next door (Collins 104). You are allowed to bring bottles that are tightly sealed (for example water bottles or travel mugs with a screw-on top) into the lab, but keep them on the counter top next to the door.

  *** You are not allowed to place them on the optics table! Any idea why?**

- Optics equipment should be kept clean. Imagine viewing the world through very dirty glasses all the time. While this is rather unpleasant for you, it can be even worse for optics and lasers: Dirty optics can get permanently damaged if high-intensity laser light is directed onto them. So please take off dirty shoes (for example if you just walked to campus and they are wet) and leave them in one of the cubby holes in the Physics Lounge. **Please also bring a pair of simple, cheap, clean shoes that you keep in the cubby holes and that you only wear in the OPTIX lab or our other research labs.** In addition, please try to avoid dust and other dirt as much as possible.
- In this lab you will use lasers. Watch the video and read the additional *Laser Safety Materials* before coming to lab. There will be a test about laser safety before you begin this module, and **you must pass it** before you will be allowed to work in the lab.

- Most of the laser beams are a few cm above the optics table, which puts them pretty much at eye height for someone who is sitting down. So, **no chairs and no sitting in this lab**. When you want to analyze your data, or if you need a break, please go to the Lounge.

- Fingerprints can easily damage optics. Always think carefully about which part(s) of an optical piece of equipment you can touch safely and which one(s) you should never touch. **Please wear gloves** whenever you handle research-grade equipment, for example when you mount mirrors or lenses. You can find them in the cabinet next to the door. Please note that we recycle these gloves, so collect them in the appropriate box after you are done using them.

- **Read through the whole manual before coming to the OPTIX lab. Work through the boxes in sections 1 through 6 of this module, as well as all the boxes marked with a *, and complete them before coming to the lab. Be prepared to discuss your results with your group members and your instructor. This counts as your pre-lab.**

- **If you damage anything, please tell your instructor *immediately*.** While we of course try to avoid damaging the equipment, accidents can happen. Please don't try to cover up any damage; that only makes life harder for us as we try to figure out why something is no longer working. Tell us exactly what happened, and we can either fix it or replace the equipment quickly.

*** As preparation for this module, write down everything you remember from the optics unit in Intro Physics II or from previous classes, for example in high school (any relations, sketches, key words that pop into your mind). If you can connect them in a meaningful way, even better! And now - have fun in the lab!**

5 Introduction:

> "...[O]ptics and photonics are technologies central to modern life. An understanding of integrated circuits, displays, fiber communication, medical tools, and solar power all require a deep understand of underlying optical principles, as outlined in the 2012 report of the National Research Council [*Optics and Photonics. Essential Technologies for Our Nation.* Committee on Harnessing Light, National Research Council (2012)]. Lasers in particular are used in almost every aspect of research and everyday life, ranging from powerful yet precise drills in industry to applications in medicine for noninvasive diagnostics and faster, safer, more localized treatment. Lasers are used in Internet and GPS communication, in LIDAR (Light Detection and Ranging) to detect pollution in the atmosphere, and in bar code scanners and CD/DVD readers. They become more relevant in a world that relies on online data storage to provide safer means of encrypting data (quantum cryptography), and they help us understand more about the world we live in, from the universe (e.g. through the use of laser guide stars and spectroscopy of astronomical objects) to chemical reactions (by freezing them in time with ultrafast pulsed lasers) [*Atoms, Molecules, and Light: AMO science Enabling the Future.* Committee for an Updated Assessment of Atomic, Molecular, and Optical Science. National Research Council. ISBN 0-309-08613-2 (2002)]. At the same time, optics is highly accessible to students of all ages, making it an ideal topic to capture and cultivate scientific interest and curiosity. In fact, UNESCO has declared 2015 the "International Year of Light and Light-based Technologies" [UNESCO: `http://www.light2015.org/Home.html`]." [NSF IAP grant #1505919, OPTIX]

In this module you will learn the basics that are necessary to successfully complete more advanced modules, and to succeed in our research labs and in a career in a STEM (Science, Technology, Engineering, Math) field after graduating from Willamette. We will begin with a brief section on how to properly handle research-grade optical equipment, which is more delicate than the teaching equipment you have used so far. We will then talk about lasers and other light sources, dive into mirrors and optical alignment, and lastly lenses, which find applications in all sorts of optical instruments (think for example of a telescope or a microscope). Lenses are used to collimate laser beams or to focus them. But even in everyday life they find numerous applications, like in your glasses or contact lenses. You will learn how to pick the right lens for your application and how to align it correctly. You will also see several special lenses, like those that compensate for certain aberrations, or those that only act like a lens in one of the two directions, so-called *cylindrical* lenses. We will then review the single and double slit to learn more about diffraction gratings that find applications in spectrometers. And lastly, you will learn about light polarization and its uses. You will even learn that you can see polarization with your naked eye!

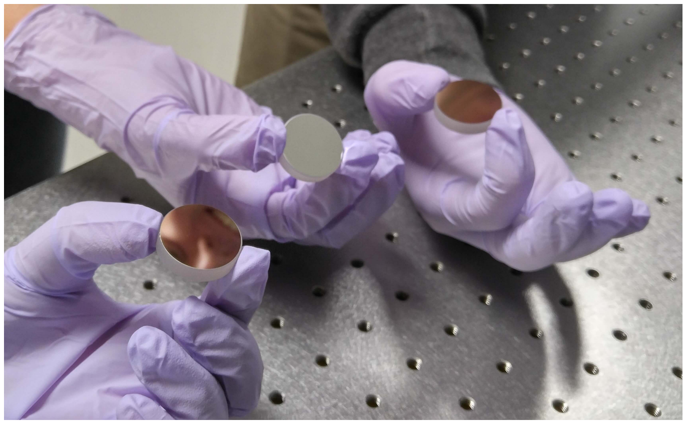
6 How to handle research-grade optical equipment:

The golden rule of optics is: Don't touch it with your bare hands. Research-grade optical elements like lenses or mirrors very often come with special coatings that reduce the reflection of light of a certain wavelength (so-called *Anti-Reflection Coatings*), which allows you to send a laser beam over multiple elements without losing significant amounts of power. When you touch such a coated element with your fingers you deposit some of the oils that your fingers produce naturally onto the element - or in other words, you leave a fingerprint. And fingerprints can be surprisingly difficult to remove, especially if they have been on the element for a while since the oils "etch" their way into the coating and destroy it. Sometimes you can save the optical element if you clean it quickly (we'll tell you in a moment how), but in some cases even that is not possible because the element is so delicate; an example of this would be a diffraction grating (you will encounter them later in this module).

Note: You will see several boxes throughout this manual. **Blue boxes** contain tips and tricks, while **yellow boxes** are (mostly) empty and are meant for your own notes, and **green boxes** encourage you to play with and explore the equipment. Even if you print this manual with a black-and-white printer you will be able to easily distinguish the boxes: Yellow boxes typically have no header, while blue boxes always have the header "How to..." and green boxes have the header "Let's play with it".

How to hold optical elements safely:

Put on gloves. You can find them in the upper cabinet next to the door. Keep in mind that we recycle them, so please place them in the labeled box once you are done using them. Grab the optical element *gently* from the outside, touching only the unpolished part of the glass, just as shown in the photo below.

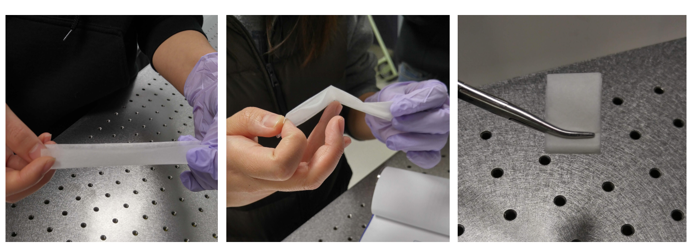


If you press down too hard it is very likely that some part of your fingers touch the outside of the actual optical element, and even with gloves that can leave some marks.

If, despite your best efforts, you leave a fingerprint on an optical element, please ask your instructor for help; they will show you how to clean that particular optical element (if possible). You can find general cleaning instructions below and on the next page. Please also watch the VIDEO called `HOW TO CLEAN AN OPTICAL ELEMENT`.

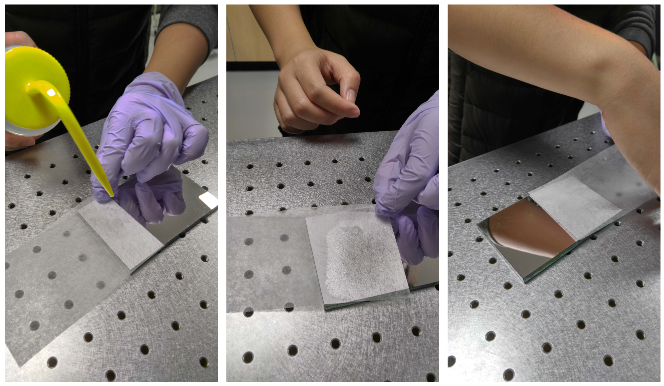
How to correctly clean (some) optical elements:

- To clean optical elements, you need clean compressed air; special optical cleaning paper, which is very fine, clean paper; a pair of small pliers (hemostats work great!); and methanol or isopropyl alcohol of high optical grade. Both alcohols are relatively safe unless you drink them or inhale large amounts of the vapor. You should avoid getting them on your skin as they dissolve the oils in your skin and dry it out quickly. For more information please read the *Material Safety Data Sheet* (MSDS), that you can find in the cabinet in which the optics cleaning supplies are stored. In most cases, isopropyl alcohol is preferred over methanol since it leaves less residue on the optical element.
- Gently blow dust off the optics using clean compressed air. We have a special oil-free compressor that is stored in the lower cabinet next to the door for exactly that purpose. Please ask your instructor for help before you use if for the first time. Make sure to hold the nozzle close to the optics without touching it, at an angle of approximately 45°, and gently blow down onto the surface. This removes any big dust pieces that could scratch the surface before you use the paper and the alcohol to clean it further, and by blowing *down* on the optics, you avoid adding significant amounts of dust to the air above the table.
- Fold the optics paper twice in half along the short side (creating a "hot dog"), taking care that your fingers don't touch the middle part of the paper; you will use this part to clean your optics, and you want to avoid leaving fingerprints on it. Then fold it in half twice along the long axis ("hamburger style"). Again, make sure that your fingers don't touch the middle part. Lastly, grab the folded paper with the hemostat such that about 2-3 mm of the middle edge are on one side of the hemostat as shown in the photo sequence below.



How to correctly clean (some) optical elements, cont'd:

- Add a few drops of isopropyl alcohol to the optics paper and, in one quick smooth motion, gently drag it over the optical element you want to clean. If the optical element is not as clean as you would like, discard the optics paper and use a new one, folding it following the method outlined above.
- In some cases, when the optical element is extremely delicate like a diffraction grating, you want to use a slightly modified method: Gently blow off the optical element with compressed air as described above. Then place a piece of optics paper onto one end of the optical element and add a drop of isopropyl alcohol onto the paper as shown in the left photo below. Gently drag the paper across the optical element. That way, you first distribute the alcohol across the full surface of the optical element, and then dry it off as you reach the drier part of the paper.



You can practice both methods on the mirror labeled 'DEMO 1'. Feel free to ask your instructor for help.

Please note that these two methods should really only be used if you see fingerprints or something similar on an optical element. Dust will be much more common, and in that case just use the compressed air to gently blow the dust off the element as described on page 5.

*** Summarize how to correctly handle research-grade optics equipment, and list a few things that you should avoid at all cost.**

7 Lasers and other light sources

Danger: You must have watched, read, and understood the *Laser Safety Materials* before proceeding. Lasers can permanently damage your eyes and/or your skin if handled incorrectly!

In most of the modules we will use lasers as our light source because they are convenient and by now relatively inexpensive, highly collimated, and coherent sources of light that come with a very narrowly determined wavelength, power, and polarization. Only occasionally will we use a white-light source such as a lightbulb or an LED.

7.1 How to pick the right laser

Picking the right laser for your application depends very strongly ... well, on your application. There is no one size fits all laser for everything. So, instead we will give you just a few things to consider when picking a laser that is just right for what you have in mind:

1. **Wavelength:** The wavelength ('color') is probably the first thing that comes to mind. By now, you can find lasers in all possible wavelength regions, from the ultraviolet (UV) below 400 nm, to the visible (400 to 700 nm), the near-infrared (near-IR) above 700 nm, or the infrared (IR) above about 900 nm.

2. **Power:** Generally, pick the lowest power that works for your application (it's just safer that way). Please review the *Laser Safety Materials* and keep in mind that power and wavelength affect the laser class.

3. **cw or pulsed:** Lasers come in two versions: As a continuous-wave or cw laser, and as a pulsed laser. As the names suggest, a cw laser emits radiation continuously, while the radiation in a pulsed laser comes in small packages, the laser pulses. These pulses can have very different pulse widths (from a Nd:YAG laser with typically a few 10 ns to a fiber laser with ps or fs pulse width), and different repetition rates (a few hertz to several megahertz).

4. **Polarization:** Most lasers come with a fixed linear polarization, but some have random polarization. In fact, one of the black Helium-Neon lasers you will use in this module has random polarization.

7.2 How to mount and align lasers

In OPTIX we will encounter two different types of lasers: Those that come pre-mounted in a nice package and laser diodes. The former class includes the Helium-Neon laser ('HeNe laser') that you will use today, and the pulsed laser from IPG that you will use in `MODULE 5 - INTERMEDIATE.` Mounting these is very easy - just use table screws and/or table clamps ('dogs'). Mounting a laser diode is a bit more involved since you not only have to get it into the driver that supplies the diode with current and stabilizes its temperature, but you also have to collimate it carefully. You will learn more about these type of lasers in `MODULE 3 - INTERMEDIATE.`
It is very important to ensure that the laser beam is level with the table surface, which means that it does not go up or down significantly over the length of the table. This, again, is to ensure everyone's safety in the lab: If the beam moved up significantly, it could easily hit someone in the eye and cause damage. Of course, using an actual level to check the alignment is tricky since you cannot balance it on the laser beam. But there are other easy ways to ensure that your laser beam is well-aligned; you will learn about them later.

7.3 Task: Comparing a laser and a lightbulb

Before we worry about alignment, let's first compare the output from a laser and from a regular lightbulb. Confirm that your laser safety goggles will protect you from light at 633 nm. You can check this by checking the 'OD' value that is printed for each wavelength range listed on the goggles. 'OD' stands for 'optical density', and that tells you how strongly the goggles block light within a certain wavelength range. For example, and OD of +7 means that the incoming light is attenuated by a factor of 10^7 after passing through the goggles. That's quite a bit! However, these goggles are only designed to protect you from stray light. You should never look directly into a laser beam with them!

Put on the goggles and mount the HeNe laser securely to the table by putting one of the small *T-nuts* (located in the screw box) into the bottom of the laser and attaching a post using a set screw as shown in the photo below.

Plug the HeNe laser into the outlet and turn it on (there's a switch at the back of the laser). Because the goggles are working correctly you will not see the laser beam. But you can make it visible, even while wearing goggles, by using one of the detector cards (shown in the above figure on the right).

The HeNe laser is a class IIIa laser, which means it can damage your eyes. In addition, there are also other student groups working in the same lab, so you **must wear your safety goggles at all times**. However, a few of the tasks in this module will ask you to take off the goggles to peek at the projection of the laser beam on the wall or on a piece of paper. Note that this is safe as long as you ensure that

1. the laser beam is level with the table and follows a straight path;
2. the laser beam is either hitting the wall directly or is being blocked by a piece of paper at the edge of the table, so that it does not proceed all the way across the room;
3. you have removed all jewelry and other reflective items from your hands and wrists and you are not reaching into the beam with reflective tools like screw drivers;
4. you don't bend down and look into the laser beam.

Please always check with your instructor first to confirm that it is safe to take off the goggles, and announce to the other students in the lab that you will take off your goggles.

Place the lightbulb next to the laser and turn it on as well. Place a piece of paper behind the laser and the light bulb, **stand behind the laser**, and **take off your goggles**.

Observe the light from the laser and the lightbulb on the paper; do not look directly into either of them! Record your observations below.

	laser	**lightbulb**
color		
divergence		
What does it look like?		

Put on your goggles. The first thing you probably noticed is the color: The laser is obviously red while the lightbulb is obviously white. Let's investigate this some more using a *spectrometer*. The spectrometer you'll use is the *Mightex BD1*, which covers the spectral range of about 300 to 700 nm with a resolution of about a nanometer. For now, you can treat it as a black box that tells you the spectral composition of the light it measures. In MODULE 4 - INTERMEDIATE. you will build a small spectrometer that uses the same principle as the Mightex. Note that we have only one spectrometer, so you have to coordinate with the other lab groups (or do this part of the module together as one big group). Please also watch the VIDEO called HOW TO USE THE MIGHTEX SPECTROMETER on our website.

How to obtain a spectrum with the Mightex spectrometer:

- Plug the USB cable into the computer and open the program 'Mightex' from the desktop.
- Click on the 'calibration' button (near the top right hand side) and select the calibration file 'BD1'. This converts the pixel position on the CCD camera into an actual wavelength reading.
- Then click the 'play' button near the top middle of the screen ('acquire spectrum continuously'), and the spectrum should appear on the screen. At this point, it'll probably just a random zigg-zaggy line.
- The light enters the spectrometer through a fiber optical cable (that's the green 'wire' that is attached to the spectrometer). Be careful - fibers have glass cores and can easily break when bent too much, i.e. when the radius of the bent ring is less than about 5-10 cm. Don't lean on the fiber or drop tools onto it since this, too, can permanently damage it. While coupling light into a fiber is typically rather involved since the light entering the fiber must have the correct diameter, angle, and phase when it hits the fiber, the spectrometer uses a *cosine corrector*, an optical diffuser that allows you to collect light from the full 180° cone. By scattering the incoming light, cosine correctors couple only a small fraction of the incident light into the fiber, but because the Mightex uses a CCD camera it is very sensitive and does not require much light to give you a good signal.
- Carefully move the fiber into the laser beam while at the same time looking at the spectrum. As soon as you see a spike appear, stop moving the fiber. You don't want to mount it directly in the laser beam because that would saturate the CCD sensor immediately, which could potentially damage it. The spectrometer is sensitive enough to pick up just a few photons from the edge of the beam. Once you see a spike in the spectrum that is sufficiently large compared to the background noise you can lock down the cosine corrector.

Turn off the lights and record the spectrum of the HeNe laser and of the lightbulb. Save screenshots of both and attach a printout to this manual. Compare the two spectra; what is similar/different?

Let's play with it!

[Note: These green 'Let's play with it!' boxes will introduce you to what physicists mean when they say "I played with the equipment."] You just observed that the two spectra look very different: The spectrum from the lightbulb is rather broad while the spectrum from your laser is very narrow. But there is a way to narrow the lighbulb spectrum: A filter.

Place the red filter directly in front of the cosine corrector and record the spectrum of the lightbulb again. What changes? Does this filter turn the lightbulb into a laser? Explain why/why not.

8 Mirrors and basic alignment procedures

In this section we will introduce you to mirrors and how to use them to modify the path of a laser beam.

8.1 How to pick the right mirror

There are two different basic types of mirrors: **Plane mirrors** and **spherical (or other curved) mirrors**. Let's first look at plane mirrors: Imagine that a plane mirror is attached to the table, and that you shine a laser beam directly perpendicular onto the mirror.

*** Where does the reflected beam end up?**

This is a situation you typically want to avoid.

*** Can you imagine why? Hint: Think about what happens when the reflected beam makes it all the way back to the laser.**

Now imagine you have an angle θ between the incident laser beam and the *normal* to the surface of the mirror. What happens now? Do the experiment by placing one of the big rectangular mirrors labeled as `'DEMO 1'` onto the table (don't just hold it in your hand!) and sliding it into the path of the laser beam. Making sure that the laser beam does not move up or down, change the angle under which the laser beam hits the mirror.

Record your observations, including a small sketch.

This, of course, is the famous **Law of Reflection:** "The angle of incidence is the same as the angle of reflection (as measured with respect to the normal to the surface)." The last part in parentheses is actually very important: While here, in the case of simple reflection, it doesn't matter whether you pick the angle between the surface and the laser beam, or the one between the normal and the laser beam, because the incident and the reflected angles are identical and thus either of these two pairs of angles will be equal, the choice of angles matters significantly once you consider *refraction* into a material (like a lens; we'll come to this in a moment). So make it a habit to *always* use the angle between the laser beam and the normal to the surface.

Now that you've seen plane mirrors in action, let's look at some curved mirrors, in particular **spherical mirrors**. There are also parabolic or elliptical mirrors, which are just other types of curved mirrors. They follow the same principles we'll derive here in a moment, so we won't discuss them separately. If you are interested in what they do, check out for example Thorlabs' website at `www.thorlabs.com`. You can find them under 'Products Home' → 'Optics' → 'Optical Elements' → 'Mirrors'. Spherical mirrors come in two versions: as **converging ('concave')** and **diverging ('convex')**.

Let's play with it!

Take the big mirror labeled as `'DEMO 2'` and hold it a few cm away from your face with the mirror curving away from you, and then slowly move it away until it is at arm's length.

Describe what you see.

Now turn it around so that the mirror is curving toward you and repeat.

Again, describe what you see.

Spherical mirrors can act as lenses: An ideal converging or concave mirror focuses parallel rays of light to a single point, just like an ideal lens. This point is related to the curvature of the mirror: If you picture the spherical mirror as part of a circle, then the point onto which the light is focused is the center of that circle. Therefore, spherical mirrors are often characterized by their *Radius of Curvature* R, and as you may remember from the optics unit in Intro Physics II or from highschool physics, R is related to the focal length of a lens f through $f = R/2$. Similarly, an ideal diverging or convex mirror "defocuses" the light, just like a diverging lens does. It, too, can be characterized by the radius of curvature (which for diverging mirrors is negative). If you again picture the mirror as part of a circle, then in this case you are looking from the *outside* at the circle, and the radius of curvature is still the radius of that circle. Diverging mirrors are often used in cases where it is important to "see around the corner", for example on street crossings with poor visibility, since they allow you to gather light from a larger angle.

*** Draw a concave and a convex mirror and include a few light rays to show how they bounce off the mirror (hint: over a sufficiently small region, a spherical mirror is almost plane). Carefully show where the angles are located and what their relationship is.**

Now use one of the spherical mirrors (`'DEMO 2'`) and roughly measure the radius of curvature using the flashlight from your phone (or another LED light source).

Do you think it is easier to use the converging or the diverging side of the mirror? Record your value, including an estimate for its uncertainty and a brief description of what you did.

Another thing to consider is a mirror's **reflectivity** at a given wavelength. Take a thick glass slide and attach it to a mount or post using double sided sticky tape. Make sure that it is perpendicular to the table and angled at about 45° with respect to the incoming laser beam. You should observe that the majority of the laser beam passes through the glass slide, but that a small fraction is reflected.

What angle of reflection do you expect? Thus, where, relative to the laser beam, do you expect to see the reflected beam? Draw a sketch.

Now use a power meter to measure the power of the beam before it hits the glass slide (call this P_0), the power of the beam that is transmitted (P_t), and the power of the beam that is reflected (P_r). To use the power meter correctly, turn it on and make sure that the wavelength is set to 633 nm, the wavelength of your laser. This is important because the power meter measures the amount of heat that is deposited by the laser beam, or in other words, the energy that the laser beam deposits. This energy is the sum of all the energies of the single photons. The more photons, the more energy. As you probably remember from Modern Physics, the energy $E = hf$ for a single photon, where h is the Planck Constant, and f is the frequency of the photon. Thus, the total energy deposited onto the sensor is $E_{tot} = Nhf$, and as stated before, the larger N, the more energy, and thus the more powerful the laser beam. From this relation it becomes clear that, in order to be able to solve for N which tells you the power of your beam, you need to know the frequency (or, equivalently, the wavelength).

Record your values, including an estimate for their uncertainties, in the space below. Is $P_0 = P_r + P_t$? If not, why not?

You should have found that about 4-7% of the incident light is reflected by the glass slide. That's a good figure of merit to memorize. You may also have noticed that there is not just one reflected beam, but actually several, and that not all of them have the same intensity. If you haven't noticed it yet, look more closely again (it may help to **take off your goggles** and look at the reflected beam on the wall).

Can you explain why there are multiple beams? Hint: Remember that this is a *thick* glass slide!

Imagine what happens to your laser beam when you reflect only a few percent of the incident light; it gets very weak very quickly. Or in other words: a glass slide is a really poor mirror. So, to improve the reflectivity and thus reduce the losses when reflecting off a mirror, companies add a coating to the mirror. There are two types of coatings, **metal** and **dielectric** ones. Carefully take out the two mirrors labeled as `'DEMO 3'` and `'DEMO 4'` if you want to see an example of each. Metal mirrors are perfect for a wide range of applications, and in fact, you will use silver-coated mirrors throughout this module. They are great choices for the spectral range of 450 nm to about 20 μm! There are also gold-coated mirrors (optimized for 800 nm to 20 μm) and aluminum-coated mirrors (250 nm to 20 μm). While it may seem that the aluminum mirror is the best choice overall since it covers the broadest range, that's actually not the case. To see why, go back to Thorlabs' website and search for mirrors with these three types of coatings. Find the 'Graphs' tab and compare the three graphs. For now, you can focus on the green curve for 'unpolarized' light since we haven't talked about polarization yet. We will revisit this issue toward the end of this module.

*** Which mirror would you pick for 300 nm? Which for 600 nm? Which for 1300 nm?**

Another type of coating is a dielectric coating. Here, instead of increasing the reflectivity of the mirror using a metallic coating, similar to your bathroom mirror, a thin layer (or several) of a transparent material is deposited. The key is that this material has a different *index of refraction* compared to both air and the glass substrate. You can think of the index of refraction (or refractive index) as a measure of how 'easy' it is for light to travel through a given material. Air has a refractive index of (very close to) one, and light travels at the speed of light, c, through it. As the refractive index increases, the speed of light decreases. It's kind of like entering molasses - the more viscous the molasses (the higher the refractive index), the more difficult it is to move through it, and thus the slower you have to go (the speed of light decreases). The index of refraction also plays a key role when light enters from one medium into another. In other words, when it refracts at a boundary. Consider a beam of light coming from the left under some angle θ_1 with respect to the normal and entering another material.

*** Let's say the index of refraction of the first material is n_1, and of the second material n_2. Draw what happens for the three cases $n_1 < n_2$, $n_1 = n_2$, and $n_1 > n_2$.**

The relation between the incident and the refracted angle is of course given by **Snell's Law**, $n_1 \sin\theta_1 = n_2 \sin\theta_2$. Now you understand why it is so important to *always* pick the angles with respect to the *normal* of the surface, and not with respect to the surface itself, just as we pointed out when we talked about simple reflection.

*** Of course, you could take these angles, but you would have to rephrase Snell's Law accordingly. Derive the modified expression.**

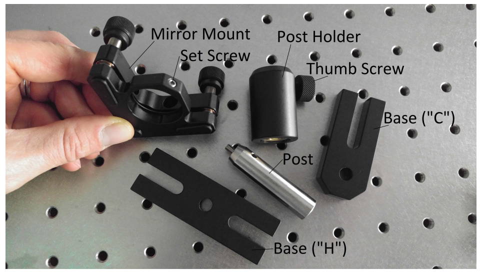
In order to understand how a dielectric coating works, consider a thin coating of index n_c on top of the glass (n_g). Imagine now that you send in a beam of light from air (n_a) under an angle of θ_1. For most anti-reflection (or AR) coatings, $n_a < n_c < n_g$.

*** Carefully draw this situation and make sure to define all your variables.**

Keep in mind that the laser beam can reflect off the air-coating transition and off the coating-glass transition! So that means that you get *two* reflected beams that move in the same direction. But because one of the beams has traveled a longer distance - through the coating to hit the glass - there is a phase difference between them. Note: In addition to this phase difference due to the different paths, you also pick up a phase of π whenever your beam reflects off a medium with a larger index of refraction. **Draw two representative rays into your sketch above.**

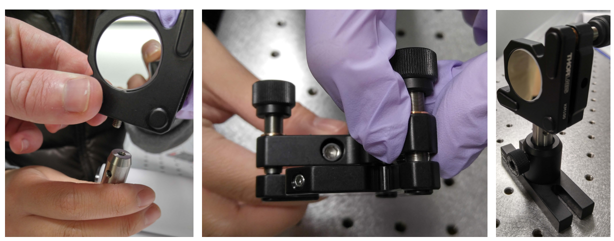
*** Derive an expression for the thickness d of the coating such that light of wavelength λ has the largest possible reflectivity (i.e. zero transmission).**

Now that you have a better understanding of a what a mirror is and what it does, let's get hands-on again and learn how to mount and use it in an actual optics lab. Since mirrors and other optical elements are quite delicate and need to be aligned precisely, we use mounts to hold them in place and aid us in the general alignment procedures outlined below. Most mirrors will sit in so-called kinematic mounts. These mounts consist of five pieces: The actual mount, a black anodized aluminum structure with a 1-inch hole and two or three screws at the back; a small set screw at the top of this mount that allows us to hold the mirror in the mount securely; a half-inch diameter aluminum post of some length; a black post holder of some length; and a black base that looks either like the letter C or H, see the photo below.



How to mount a mirror in a kinematic mirror mount:

- You can find a `VIDEO` tutorial called `HOW TO MOUNT A MIRROR` on our website.
- To insert the mirror, loosen the set screw with an Allen wrench.
- Wearing gloves, gently drop the mirror into the mount until its back is resting against the back of the mount.
- Tighten the set screw until the mirror is held securely.
- Slide a small screw from the top into the hole on one side of the mount and screw the screw into the post (you have to remove the small set screw first). Make sure to tighten this screw.



- Connect the base to the post holder by inserting a 1/4-20 table screw into the countersink hole of the base and screwing it into the bottom of the post holder. Again, make sure to tighten this screw. Insert the post into the post holder. The big thumb screw on the post holder is spring loaded, which means that it will hold the post in place nicely even if it is only tightened slightly.
- Adjust the big thumb screws at the back of the mirror mount to their mid-range; that gives you the most flexibility when using them to align the mirror.

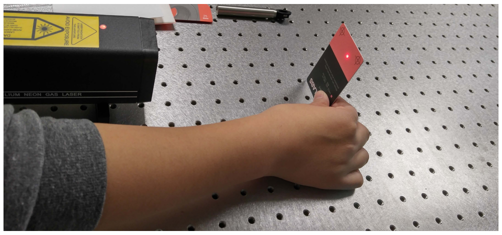
Speaking of alignment - what do these screws do? Rotate them, one by one, and record your observations. A sketch in which you indicate which screw you are talking about might be helpful.

Now that the mirror is safely mounted in the mirror mount you can attach it to the table using a 1/4-20 screw. Always make sure to lock all optical elements down securely, and **never just place them on the table since it is very easy to knock them over, potentially damaging them, or ruining your careful alignment**. Always make sure to double check that all the screws that hold the base, mount, post, and mirror mount together are securely tightened. As you read earlier, it is important to keep the beams as parallel to the optics table as possible, and align them in straight lines. You'll now learn how to do that. Please also watch the `VIDEO` called `HOW TO STRAIGHTEN AND LEVEL A LASER BEAM`.

How to ensure that laser beams follow a straight and level path:

- **To ensure that a laser beam is level with the surface of the table:** Place a piece of paper, one of the detector cards, or an iris onto the table close to the laser and mark the height of the laser beam on it. Then move the paper/card/iris backwards. If the beam moves away from your mark, up or down, adjust the mirrors until you hit the mark again. You will learn how to adjust mirrors and practice this in just a moment in the following section.

- **To ensure that the laser beam follows a straight path:** You can use the rows of screw holes as a guide. Gently lean over the table and look down onto the rows of screw holes. Then move the detector card or piece of paper backwards, thus tracing out the path of the laser beam. Looking from above you can easily see if the laser beam veers to the left or right. Again, use mirrors to correct the path of the beam.



Keeping the laser beams straight and level with the table surface does more than just make the beam path look tidy; it is an essential safety measure to ensure that the beam can't get into anyone's eye. Keeping the beams straight also serves another purpose: Aligned this way, a laser beam will always make 90° turns when it hits a mirror. That is good, because most mirrors tend to do weird things with the polarization of a laser beam unless the laser beam reflects off the mirror at either 45° or 90°. You'll learn more about the polarization of a laser beam in the last section of this module.

8.2 Task: Learn how to align a laser beam

We'll now put your alignment skills to the test. Attach the HeNe laser safely to one corner of the table, **put on your goggles**, and then turn on the laser. Confirm that it is going straight and approximately level with the table. Insert one mirror a few cm after the laser and make the beam turn 90°. Make sure that the beam hits the mirror roughly in its center, and ensure that it stays parallel to the table after bouncing off the mirror. Lock the mirror down and tighten all screws. Then insert a second mirror, again after a few cm, and turn the beam another 90° such that it is now parallel to the original beam. Lock both mirrors down tightly. Again, ensure that the beam is aligned straight and stays level with the table.

Check with your instructor when you are done and record any observations, tips/tricks, or concerns. Sketch your final setup (bird's eye view) here.

8.3 Task: Learn how to change the height of a laser beam

In reality, you sometimes have to slightly raise or lower the height of the laser beam, for example when you send the laser from one piece of equipment to another. Let's practice this. Your goal is to modify your current setup such that the final beam is about 5 mm higher than the original laser beam, but is still traveling in a straight line and parallel to the surface of the table.

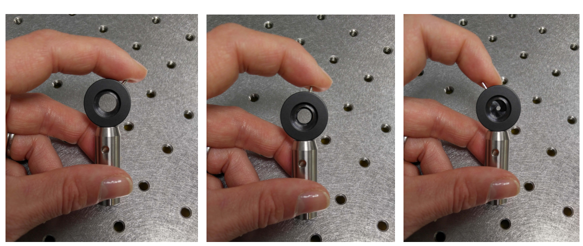
Discuss this with your neighbor and record your battle plan, including a quick sketch of the setup.

Then put your plan to the test! Align the mirrors and confirm that your planned setup indeed produces the desired result. Note: If you reach the end of the thumb screw that rotates the mirror mount think about how you can modify the spacing of your mirrors to avoid that.

If you had to modify your setup, make sure to write down any chances and reasons for these changes here.

8.4 Task: Learn how to "walk a laser beam"

A laser beam is essentially a line in space. And as any line, it is completely defined by two points. That means, if your laser beam has to follow a very specific path, you need at least *two* fixed points in space through which the laser beam must go. Let's simulate those two points with two irises of different height. An iris is a variable aperture. You can open and close it by gently pressing tangentially on the small lever as shown in the photo sequence below.



Practice this a few times. Then attach the irises to posts and mount the posts in two post holders with bases. The second iris should be about 5 mm higher than the first one. Place the first iris approximately 3 inches after your second mirror, and the second iris approximately 6 inches after the first iris. Your goal now is to shoot your laser beam through both irises. Please add a beam block (for example a piece of paper) a few inches after the second iris to catch any stray beams before you proceed. Then give it a shot!

Explain how you want to go about aligning the laser beam. Then carry out your procedure and briefly record if you were successful or not.

If you have never done something like this before, chances are you will have more or less randomly moved the screws on the mirrors with probably little to no success at all. But notice that we asked you to place the irises after *two* mirrors? There's a reason for that, and it again has to do with the two points that define a line: With only a single mirror, the point at which the laser beam hits the mirror is of course fixed; you can't change that point by rotating the screws since that only changes where the beam goes *after* it reflects off the mirror surface.

But what changes when you use two mirrors? Draw a sketch and explain carefully (what does each mirror do?).

What you just discovered is generally called 'walking the beam': Two mirrors allow you to shift the whole laser beam in space, instead of just changing its pointing. There are multiple ways of how to systematically walk a beam. Here's one of them. Please also watch the VIDEO called HOW TO WALK A LASER BEAM on our website.

How to 'walk' a laser beam:

- This is an *iterative* procedure, which means that you have to repeat it a few times, and that after each iteration you should be closer to your alignment goal, e.g. of sending the laser beam through two irises.
- To make things easier to follow, we will call the mirror that is closest to the laser 'mirror 1', and the one that is farther away 'mirror 2'.
- Similarly, we will call the iris closer to the laser 'iris 1', and the one farther away 'iris 2'.
- **You will always use 'mirror 1' ['mirror 2'] to align the beam through the center of 'iris 1' ['iris 2'].**
- To start, close 'iris 1' almost completely and use 'mirror 1' to bounce the beam off 'mirror 2' and center the beam on 'iris 1'. Do not change 'mirror 2'. You can check the alignment by slowly opening and closing 'iris 1' and observing the beam after the iris. The beam should appear symmetric with respect to the iris. If, for example, one side of the beam disappears before the opposite side when you close the iris, you know that the iris is not centered well enough.
- When you are satisfied with this alignment, open 'iris 1' and observe the beam as it hits 'iris 2'. Chances are, it is not going through the center of 'iris 2' yet. Close 'iris 2' almost completely and use 'mirror 2' to center the beam on 'iris 2', just as you did with 'mirror 1' and 'iris 1'. Do not rotate the screws on 'mirror 1' at this point.
- Repeat multiple times until the beam goes through the center of both 'iris 1' and 'iris 2'. (Note: Before you repeat these steps, read on and fill out the next two boxes.)

After one iteration, close 'iris 1' again and describe what has happened to the position of the laser beam on 'iris 1'.

Iterate one more time and then again describe what has happened to the alignment through 'iris 1' after this second iteration.

Iterate a few more times until the laser beam passes through the centers of both irises.

Describe what happens to the laser beam in each of the iteration steps. Then describe in very general terms how you paired up mirrors and irises.

Let's play with it!

Now that your beam is going through both irises, is it still parallel to the table? If not, can you make it parallel? [Hint: Simply removing the second iris and keeping the beam at a constant height above the table is *not* the correct answer. Remember, you started by requiring your beam to go through both irises!]

Describe how you did it and confirm experimentally that your idea indeed works!

9 Lenses

A lens is essentially just a piece of glass that is thicker on one end and thinner on another. There are two basic types of lenses: Converging (or convex) lenses that are thicker in the middle and thinner toward the edge, and diverging (or concave) lenses that are thinner in the middle and thicker toward the edges. 'Converging' and 'diverging' are names that are easy to memorize once you know what a beam of light does when it hits these lenses, but 'concave' and 'convex' are a bit more difficult to remember. This might help you: "My neighbor's dog Rex loves food and is convex." That dog clearly is thicker in the middle and thinner toward the edge! Alternatively, you can picture the opening of a cave, which has the same shape as a concave lens.

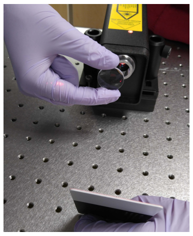
Your first task is to figure out what each of these lens types does. **Put on your goggles** and ensure that your laser beam either directly hits a wall or that you have attached a piece of paper at the edge of the table that blocks the beam. Insert the beam expander directly after the laser. You will learn later how it works; for now, all you need to know is that it widens the laser beam by a factor of 20. That'll make the following experiments easier. If you don't have a beam expander, place a +50-mm lens directly after the laser and place a +1000-mm lens a distance of 1050 mm away from the first lens. Make sure that the beam hits both lenses in the center (you will learn later how to do this correctly. For now, please ask your instructor for help.)

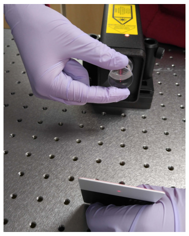
Let's play with it!

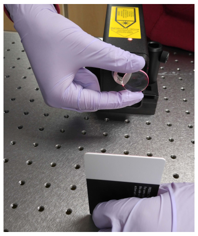
Use the two lenses labeled as `'DEMO 5'` and `'DEMO 6'` and figure out which one is converging and which is diverging. Note: You are allowed to touch these lenses while wearing gloves (but *only these lenses*). Then hold them in the path of your laser beam such that the beam hits the lens pretty much in the center.

Observe the beam on a detector card across the full length of the table, starting directly behind the lens. Describe what happens when it passes through a diverging compared to passing through a converging lens. Also rotate each of the lenses in your hands about an axis parallel to the laser beam (no tilting) and describe what you observe.

Place the `'DEMO 5'` lens in front of the wide beam. Then move it perpendicular to the laser beam such that the beam hits the lens off-center, either further to the left or further to the right and no longer in the middle as shown in the photos below. If you find it too difficult to hold the lens in your hands, you may mount it in a lens holder (look for the 'How to mount a lens' box below).







Observe the laser beam on the detector card at a distance close to the focal point of the lens and describe what happens when you move the lens left and right. In particular, compare the location of the focal point (i.e. its distance from the lens) when the beam hits the lens further to the left, directly in the middle, and further to the right of the lens. A sketch may help. Note: This is a pretty subtle effect!

The distortions you see are called **lens aberrations**, and there are several different types. The particular one you observe here is called ‘spherical aberration’, and it appears when a laser beam is not going through the center of a lens. In that case, rays that hit the lens farther away from the center are bent more strongly and come to a focus closer to the lens compared to rays that hit the lens in the center. This leads to a smeared-out focus and an overall distorted beam. Wikipedia actually has a nice article on lens aberrations. Search for ‘Optical Aberration’ to find it. [Note: This article is a pretty reliable source of information because lens aberrations are important for photographers, and there are many competent amateur photographers out there. And that means that the article has been checked repeatedly by many people who know their craft.] In this article you can also learn about other types of lens aberrations, like chromatic aberration or coma.

Spherical aberration can become very noticeable when you use a wide laser beam and a small lens. In order to avoid spherical aberrations, use lenses with a diameter that is at least twice as large as the diameter of the laser beam. [Mathematically, this ensures that you can use the paraxial approximation of optics.] There are also special types of lenses called ‘aspheres’ or ‘aspherical lenses’ that compensate for spherical aberrations. `‘DEMO 7’` is such a lens (please treat it carefully, it is quite pricey).

Let’s play with it!

Repeat the previous exercise with this aspherical lens and again observe the laser beam after the lens at a distance close to the focal point as well as at a distance far away. Comment on the shape of the beam and compare it to the shape it had after passing through the `‘DEMO 5’` lens. Note: This is a subtle effect!

Remove the lenses `‘DEMO 5’`, `‘DEMO 6’`, and `‘DEMO 7’`, and put them back in their respective containers. Then find the lens labeled as `’DEMO 8’`. This is a so-called **cylindrical lens**.

Let’s play with it!

Explore its properties by placing it into the laser beam (center it nicely) and observing the beam at a few distances after the lens.

Record your observations. Again, rotate the lens in your hand about an axis parallel to the laser beam and comment on the shape of the laser beam while you do this. Compare this observation to what you found for the converging and diverging lens. Record your observations.

Now that you have gained some intuitive understanding and hands-on experience with lenses, let us dive a little deeper. While lenses have many applications, their main purpose is to **alter the collimation** of a laser beam. A beam of light is called *collimated* when its rays are perfectly parallel. Unless you place an optical element into the path of such a perfectly collimated beam, it will stay collimated forever, meaning that rays of a collimated beam will never come to or diverge away from a single point. This is an over-simplification; there are no perfectly collimated laser beams in real life. You'll learn more about these real-life laser beams in `MODULE 5 - INTERMEDIATE.` However, we can produce laser beams that are fairly well collimated.

For example, observe the light from the HeNe laser over a large distance of several meters. Would you call this laser beam collimated? If not, why not? If so, over which distance would you call it collimated?

If a non-collimated laser beam converges to a point, that point is said to be a *focal point*.

Give an example of how you can create such a focal point, and demonstrate it experimentally using any of the 'DEMO' lenses you have used so far. Then think about a *perfectly collimated beam*. At which distance from the laser is the focal point of such a beam?

For the lasers you use in this module, the horizontal and the vertical location of the focus is nearly the same. But for many lasers, in particular diode lasers that you'll encounter in `MODULE 3 - INTERMEDIATE.` the focal point in the horizontal and in the vertical direction are not at the same location. This is another form of aberration called *astigmatism*. You may have heard that term before if you are wearing glasses. Your eye actually can be astigmatic, and your optometrist will prescribe glasses that use cylindrical lenses to compensate for that effect.

One last comment before we move on: A common mistake is to use 'collimated' and 'focused' interchangeably. Be very careful about that: Collimated means that a beam has the same width everywhere, whereas focused means that it comes to a focus somewhere. Thus, they are pretty much exact opposites of one another!

Sketch and label a collimated and a focused laser beam.

9.1 How to pick the right lens

Picking the right lens depends again on your application, but here are a few general things you should consider:

1. **Converging vs. diverging vs. cylindrical:** Do you need to collimate a diverging [converging] beam? Then you need a converging [diverging] lens. Do you need to widen a beam? Then use a diverging lens. If you need to generate a tight focus, use a converging lens. If your laser beam is collimated in one axis but not in the other, or if you want to create a very thin but wide laser beam, a cylindrical lens might be a good option.

2. **Coated vs. uncoated:** As with mirrors, lenses come as coated and uncoated. For most applications, you want to reduce the reflections off the lens surfaces, so an anti-reflection coating might be a good choice. This is very similar to the dielectric coating we discussed when we talked about mirrors, but instead of increasing the reflection off the surface, here, it is used to decrease the reflections (so $\Delta\phi = \pi$). However, if you use very intense laser sources, you may instead

want to go with an uncoated lens since the coating may be destroyed easily by the laser beam. In fact, that is what happened to 'DEMO 9'! To see how big the effect of coated-vs.-uncoated lenses really is, assume that you lose about 4% of the incident intensity on each uncoated surface due to reflection.

Estimate how much light you have lost after one, five, and ten lenses. Even though ten lenses sounds like much, advanced optical equipment often contains that many or even more lenses! Also estimate after how many lenses the intensity would have dropped to half the incident intensity.

3. **Specialty lenses:** Use specialty lenses that reduce the amount of beam aberrations (like aspheres or achromats) for applications that require a very nice beam profile.

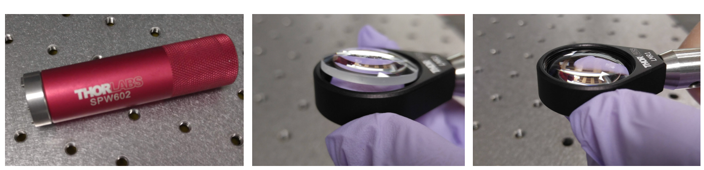
4. **Beam diameter:** To reduce the amount of spherical aberration, always make sure that your lens diameter is at least twice as large as your laser beam diameter.

9.2 How to align lenses

Next, take out one of the mounted concave and convex lenses and connected them to a lens mount, following the instructions below. Please also watch the VIDEO called HOW TO MOUNT A LENS that you can find on our website.

How to mount a lens:

- Lenses are not mounted in kinematic mounts because these mounts are quite pricey, and very often it is not necessary to be able to move the lens in quite the same way as a mirror. Instead, we will use simple lens mounts that consists of a 1-inch threaded anodized aluminum ring in which you can place the lens.
- Note that it is very easy to place a fingerprint onto the lens when dropping it into the lens mount, so make sure to wear gloves.
- If you are using an unmounted lens like the 'DEMO 5' and 'DEMO 6' lenses, use a smaller 1-inch counter ring and screw it into the first ring to sandwich the lens between the two rings and thus secure it tightly. There is a special tool called 'spanner wrench' that makes tightening the smaller ring a lot easier; it's shown in the photo below on the left. Just slide it into the bigger ring and rotate it gently until the two notches find the matching grooves on the counter ring. Then rotate the ring until you feel resistance as it hits the lens.



- If you are using a mounted lens, simply screw it into the lens mount and tighten.
- Most of the lenses that you will use in this module have one flat and one curved side. To make it easier to align them correctly (more below), please make it a habit of placing the lens with the flat side down into the lens mount, so that the smaller ring rests on the curved side. That has the added advantage that, for lenses that are strongly curved, the curved part of the lens is protected by the lens mount as shown in the above photo on the right.

As you just saw a few pages ago, sending the beam through the exact center can reduce spherical aberrations significantly! But how can you make sure that you are really going through the exact center and not slightly to the side? There are at least two ways to ensure that. Please also watch the VIDEO called HOW TO ALIGN A LENS on our website.

How to align a lens using an alignment disk:

- The alignment disk is the small, 1-inch diameter disk that you can find in the same box as the other detector cards. It is covered in the same reddish material that the detector card is coated with, and thus allows you to use it with visible and infrared lasers alike, even while wearing your protective goggles. In contrast to the rectangular detector card, it has a small hole at the center (similar to an iris).
- Slide the disk into the lens mount with the coated side facing the laser.
- Use a mirror or move the lens mount such that the laser beam is passing through the hole in the center.
- Make sure that the lens is aligned perpendicular to the laser beam.
- Lastly, lock the lens down tightly and remove the disk from the lens mount. A little bit of blue tape might help in case it got stuck.

Note that one of the instructions in the last box told you to verify that the lens is *perpendicular* to the laser beam. That is important since a tilted lens (with respect to the laser beam) introduces beam aberrations. Verify this experimentally!

Let's play with it!

Intentionally tilt the lens by a large angle, then follow the alignment procedure described above (minus the "perfectly perpendicular", of course). Observe the laser beam after the lens and describe what you see. Compare this to a well-aligned lens.

Even without an alignment disk you can ensure that the laser beam passes through the center of the lens.

How to align a lens without an alignment disk:

- Just as before, you have to make sure that the lens is aligned perpendicular to the laser beam.
- Move the lens out of the beam and place a piece of paper or one of the detector cards at least 15 inches away from the position where you want to put the lens. Secure it tightly so that it can't move and mark the position of the laser beam on the card. Note: Please don't use permanent markers or pencils on the card; use blue tape instead.
- Then insert the lens and roughly center it.
- Move the lens left and right until the laser beam hits the same spot as before. Since the lens affects the collimation of the laser beam, the diameter of the beam will no longer be the same, so just make sure that the *center* of the beam that has passed through the lens lines up with the *center* of the spot you marked on the card.
- Lock the lens down tightly and loosen the thumb screw on the post holder. Move the lens up and down until the center of the spot on the paper or card is at the same location as the center of the spot you marked on the paper or card. Lock down the thumb screw.

As we have already mentioned, most of the lenses you will use in this and future modules have one plane and one curved side. They are called 'plano-convex'. We already talked about how to mount them in the lens mounts such that it is obvious which side is the curved side. When inserting lenses into a laser beam, make sure that the curved side always faces to the side of the laser beam that is collimated (or more collimated). This leads to an overall better beam profile, although the effect is too subtle to see with the naked eye.

Sketch the orientation of a plano-convex lens when you use it to (a) focus a collimated laser beam and (b), to collimate a diverging beam.

9.3 The Lens Maker's Equation and the Lens Equation

The most important property of a lens is its **focal length**. We have already mentioned this property a few times, and you probably remember it from Intro Physics II or a high school physics course, but now it is time to provide some more rigorous background information.

The focal length f of a lens is determined by the refractive indexes n_l of the glass that is used to form the lens and n_s of the surrounding medium, and by the radius of curvature of the lens surfaces, R_1 and R_2: $\frac{1}{f} = (n_l - n_s)\left(\frac{1}{R_1} - \frac{1}{R_2}\right)$. This is the 'Lens Maker's Equation' since it allows a lens maker to form a lens of a given focal length by varying the material and the curvature of the lens.

*** Take your favorite optics textbook and figure out what all these symbols represent. Draw a sketch in the box below in which you define them.**

The mounted lenses you use in this module are made from a material called N-BK7, which means they have an index of refraction of $n_l = 1.517$. Put on your gloves and pick up the two lenses with 25 mm and 100 mm focal length from the lens cabinet.

Both of them are plano-convex, but what is different, what determines their focal length? And what is the radius of curvature of the plane side of a plano-convex lens?

Note: this is a very quick but not very accurate way of estimating the focal length of a lens.

Let's play with it!

Take the `'DEMO 5'` and `'DEMO 6'` lenses and very gently place one on top of the other.

What can you say about their respective radii of curvature? What is the focal length of this combined lens?

Let's play with the Lens Maker's Equation some more. Use the lens labeled as `'DEMO 10a'` for this exercise, or another unmounted lens with a focal length of 50 mm that is made from N-BK7. You will also need `'DEMO 10b'`, `'DEMO 10c'`, and `'DEMO 10d'`, which are 1-inch diameter plastic containers that contain clear liquids. Another N-BK7 50-mm lens is glued to the top of the containers to keep the liquid inside. `'DEMO 10b'` contains water, and both `'DEMO 10c'` and `'DEMO 10d'` contain *immersion oil*, a special oil that has the exact same index of refraction as the lens. You can find all of these demos in a box in an upper cabinet in the OPTIX lab.

Carefully look at the last two demos; what is different? Do you think this difference is important? If so, why?

Your goal is to roughly estimate the focal length of each of these lenses. If all of them were completely surrounded by air they would all have the same focal length of 50 mm. But the Lens Maker's Equation tells us that the focal length depends on the index of refraction of the surrounding medium as well, so we do expect different values.

Put on your goggles. Then place the `'DEMO 10a'` lens into the widened laser beam, align it nicely, and estimate its focal length by measuring the distance between the lens and the focal point. Use the detector card for this task. Note that this distance directly gives us the focal length of the lens as you may remember from Intro Physics II (collimated light/parallel rays are focused at a distance a focal length away from the lens).

Record your estimate of the focal length, including an estimate of the uncertainty of your measurement.

Remove the `'DEMO 10a'` lens and replace it with the other three demos, one at a time. You may tilt the plastic tube such that the laser beam hits the lens first and then passes into the liquid. Secure the plastic tube either by placing it on a stack of bases or by mounting it with a clamp. You can check your alignment by ensuring that the beam hits the lens in the center and that it leaves the opposite end of the plastic tube through the center as well. **Take off your goggles** and check whether or not the laser beam comes to a focus in the liquid. The liquid allows you to directly see the full laser beam (you will have to turn off the lights for this task).

Estimate the distance between the lens and the focal point just as you did above, and record your values, including their uncertainties, in the box below. In particular, focus on the two lenses surrounded by immersion oil. Explain your observations and comment on the relative size of the indexes of refraction of air, water, and immersion oil.

Another important relation that involves the focal length is the **Lens Equation**. Unlike the Lens Maker's Equation, it does not involve any design parameters like the refractive index or the radius of curvature. Instead, it relates the focal length of the lens to the location of the object and of the image that forms when you use this lens. Imagine you want to image an object that is a distance s away from a lens of focal length f. The Lens Equation then tells you that the image will form at a distance s' that is related to s and f via $\frac{1}{f} = \frac{1}{s} + \frac{1}{s'}$.

*** Draw a sketch in which you define the two distances and show where the object and the image are located.**

In Intro Physics II you learned how to construct the position and height of the image using the three special rays.

*** Review your knowledge of this, then draw the three special rays for a converging and a diverging lens in the space below. For both lenses, draw the situations $s < f$ and $s > f$ (so there should be a total of four sketches).**

In the next subsections we will focus on predicting the position of the image using the Lens Equation and experimentally verifying it by measuring the focal length and the object distance. Here are five methods of how you can determine the focal length of a lens. Several of them are quick methods that give you a good estimate, while others provide a more reliable and accurate result but take longer. You will practice all of them soon.

How to find the focal length of a lens:

- **Method 1: Radius of curvature method:** A very crude way to roughly estimate the focal length of a plano-convex lens, often only in comparison to another lens, is to look at the curvature of the lens surface. A lens with a smaller focal length has a surface that is curved more strongly compared to a lens with a longer focal length. This method works well to distinguish between the 25 mm, 50 mm, and 100 mm lenses, but fails to work well enough for any focal lengths above 200 mm or so. It also only works as long as the lenses you are comparing are made from the same material.
- **Method 2: Infinitely far away light source method:** Another quick method that leads to more accurate results is to project the image of the ceiling lights onto the floor. To do this, position yourself *directly underneath* a ceiling light and lower the lens to the floor until you see a sharp image on the floor. Make sure to look directly at the floor; do not look through the lens! Then measure the distance between the lens and the floor. This distance is roughly equal to the focal length of the lens. This method works well to distinguish between lenses whose focal length differs by a few cm.
- **Method 3: Lens Equation method:** An even more accurate way is to use the Lens Equation by forming an image of an object and measuring s and s'. Then, $1/f = 1/s + 1/s'$, or $f = \frac{ss'}{s+s'}$.
- **Method 4: Razor blade method:** This method uses collimated light and a razor blade (or another sharp knife edge) to estimate the focal length of a lens. Send collimated light through a lens and insert a razor blade such that you cover the lower half of the beam. Then observe the shadow of the razor blade on a screen about two focal lengths away from the lens. If the blade is at a distance that is smaller than the focal length of the lens, the shadow will appear from the top; if it is at a distance that is larger than the focal length of the lens, the shadow will appear from the bottom. Directly in the focus, the shadow appears from all sides at once.
- **Method 5: Tilt plate method:** Lastly, you can insert a glass slide into the laser beam and rotate it ('tilt plate method'). This tilt plate should be located somewhere between the laser and the lens. Rotate the tilt plate and observe the beam after the lens. When the distance after the lens is exactly equal to the focal length of the lens, the spot will no longer move as you rotate the tilt plate. This method can be extremely accurate, especially when you use a CCD camera to very carefully record the movement of the beam, and it is independent of the collimation of the original laser beam.

9.4 Task: Measure the focal length of a lens using the five methods

In this subsection you will measure the focal length of a lens using the five methods summarized above. Put on your gloves and select either the mounted 100 mm or 150 mm lens from the lens cabinet (do all of the following with just one of the two lenses, not with both!). Then attach it to a lens mount using the method outlined on page 23. Please also watch the VIDEO called HOW TO MEASURE THE FOCAL LENGTH OF A LENS on our website.

Method 1: Radius of curvature method: This method only really works well in comparison with another lens. With your gloves on, also pick up the 25 mm and the 50 mm lenses. Hold all three lenses such that you can easily see the radius of curvature of the convex side and note that the 25 mm lens bulges a lot more than your 100 mm [or 150 mm] lens, and that the 50 mm lens is somewhere in between. Note that this method only works for lenses of the same diameter and made from the same material.

Method 2: Infinitely far away light source method: In the blue box above we told you that the distance between the lens and the image of a far-away light source that forms on the floor is about equal to the focal length of the lens. Confirm this mathematically using the Lens Equation. Hint: think about the distances involved in this problem, in particular the distance between lens and ceiling compared to the focal length of the lens and the image distance.

*** Draw a sketch, and then show mathematically that $f \approx s'$.**

Holding your 100 mm [or 150 mm] lens gently, follow the instructions on page 28 to estimate the focal length of this lens using Method 2.

Record the value, including an estimate of its uncertainty, in the box below.

Method 3: Lens Equation method (Note: Don't spend too much time on this method!): Attach the LED to a small breadboard, connect it to a power supply and turn it on; this acts as your object. You may have to turn off the lights (use the green light for some background light) to see the image clearly. Place the lens a distance $s > f$ from the LED and find the image of the LED at a distance s'. Note that the lens has to be at the same height as the LED to get a good image.

Measure both s and s' and record the values, including an estimate for the uncertainty, in the box below. Add a sketch that shows your setup.

From your data, calculate the focal length f. Show your work. Find the uncertainty in f using the uncertainties of s and s' and the method of error propagation. As you may remember, the uncertainty squared of f is given by $\Delta f^2 = \left(\frac{\partial f}{\partial s}\Delta s\right)^2 + \left(\frac{\partial f}{\partial s'}\Delta s'\right)^2$ (this is the method of error propagation). Work this out for $f = \frac{ss'}{s+s'}$.

Method 4: Razor blade method: **Put on your goggles.** Mount your 100 mm [or 150 mm] lens on the table and align it nicely. Observe the laser beam on the detector card at least 250 mm after the lens. Carefully pick up a razor blade at a distance $< f$ and move it into the laser beam from below, so that it covers the lower half of the laser beam. Observe the laser beam on the detector card.

Record your observations. Then move the razor blade to a distance $> f$ and repeat. Add a sketch that shows parallel rays entering the lens as well as the razor blade at both positions to explain why you see what you see. You may also watch the `VIDEO` called `RAZOR BLADE METHOD` on our website.

Now slowly move the razor blade back until you are fairly certain that you are directly in the focus of the laser beam. Describe what you see on the detector card and measure this focal length.

Estimate the uncertainty of this measurement. Explain your observations and record your measured focal length, including its uncertainty.

Method 5: Tilt plate method: **Put on your goggles.** Remove the razor blade and place the glass plate into the laser beam somewhere between the laser and the lens. Watch the `VIDEO` called `TILT PLATE METHOD` on our website. Then observe the laser beam on the detector card about 250 mm after the lens.

Rotate the glass plate about an axis perpendicular to the laser beam and describe what you see on the card.

Now move the detector card to a distance of about 50 mm after the lens and repeat.

Again, describe what you observe.

Slowly move the detector card farther away from to the lens while rotating the tilt plate.

Describe what happens to the laser spot on the detector card when the card reaches a distance equal to the focal length of the lens, and use this observation to record the value of the focal length, including an estimate of its uncertainty, in the space below.

To fully understand why this last method gives you a direct measure of the focal length of the lens you have to take our upper-level Optics course!

Lastly, compare the five results to one another and to the known focal length of 100 mm [or 150 mm]. Comment on the relative accuracy of each measurement, and on when you would use each of the methods.

9.5 Task: Measure the magnification of a single lens

As you know, lenses can be used to magnify objects. Think for example of a simple magnifying glass! You will investigate this now. Your first goal is to derive a theoretical expression for the magnification M of a single lens, assuming that you have an object of height h that is placed a distance s to the left of a converging lens of focal length f. You already know that the image of this object forms at a distance s'. But what is its height h'?

* Use the Lens Equation together with a sketch that shows the geometry of the problem to derive an expression for h' *that contains only the knowns h, f, and s.* The magnification is defined as the ratio between h' and h: $M = h'/h$.

Now set up this single lens system. Use two LEDs as your object (the distance between the LEDs is the size h of your object). Find the position of the image.

Measure the size of the image h' (i.e. the distance between the two images of the LEDs) and compare it to the size of the object to find the magnification M. Then calculate the magnification using the expression you found in the previous box. Compare these two results, including their respective uncertainties. Are they in agreement? If not, why not?

9.6 Task: How to change the diameter of a laser beam

You have already encountered a way to change the diameter of a laser beam: By using the beam expander. Inside it are two lenses of different focal length that are a very specific distance apart (you'll derive this distance in just a moment). This system is called a **telescope** and allows you to change the diameter of a laser beam without changing its collimation.

*** Assume that a collimated laser beam hits the first lens of focal length f_1. At what distance to the right of the lens does such a beam come to a focus?**

*** If the laser beam is to exit the second lens perfectly collimated, at which distance from the focal point of the first lens do you have to place the second lens?**

*** Thus, what is the distance d between the two lenses in a telescope system?**

*** Draw a single ray that enters the first lens parallel to the optics axis, comes to a focus at the correct distance after the first lens, and leaves the second lens parallel, but at a different height from the optics axis. From this sketch derive a relation between the incoming height h (which is equivalent to half the width of the laser beam) and the height h' (or width) after the second lens.**

Put on your goggles. Set up a telescope system using two of the mounted lenses and convince yourself that the beam exits the second lens (reasonably well) collimated when the two lenses are the correct distance apart. If the beam is not well enough collimated, move the second lens until the beam is collimated.

Explain why this distance may be different than the distance you expect (hint: What was the key assumption you made in deriving the relation between d and the two focal lengths?) Also convince yourself that you have a focus in between the two lenses at the expected distance, and that the beam exiting the telescope can be either larger or smaller depending on whether the first focal length is smaller or larger than the second one.

While using a two-lens system is certainly the most common way of changing the width of a laser beam, at least in academia, there is another way to achieve the same result: by using a **prism** or a **prism pair**. Let's first start with a single prism to understand how that works in one dimension. You can then easily convince yourself that a *pair* of prisms can affect two orthogonal directions, and thus change the width of the laser beam.

Draw a prism with a right angle in the lower left corner, an angle of α at the top, and thus an angle of $90^\circ - \alpha$ in the lower right corner. To make life easier, assume that a collimated laser beam parallel to the optics axis and with a beam width w is incident from the left. Thus, the angle of incidence on the first (vertical) surface of the prism is zero degrees. Feel free to have a look at such a prism; it's in the optics cabinet.

Assume that the index of refraction of the prism is n, and that the index of refraction of air is to a very good approximation 1.

Find the angle of incidence on the second surface of the prism. You may focus only on the two rays that mark the width of the laser beam. Use your sketch in the previous box to help you derive this answer, but record your result here as well.

Lastly, find the angle of refraction after the prism. Express it in terms of the refractive index n and the angle α.

From your sketch and your calculations, find an expression for the width of the laser beam as it leaves the prism. Express it in terms of the initial width w, the angle of the prism α, and the index of refraction n of the prism.

Let's play with it!

Confirm experimentally that what you just derived makes sense, at least qualitatively. Place one of the prisms into the laser beam and compare the beam width before and after the prism. Note that in your derivation you assumed that the beam hits the first surface perpendicularly. For the prisms we use in this lab, however, that angle of incidence leads to total internal reflection within the prism, so you'll have to allow a small angle of incidence on the first surface of the prism to see the effect. Also, feel free to use the telescope from the previous exercise; it is easier to see the effect of the prism on the laser beam when the beam is wider.

As you just saw, a single prism can change the width of a laser beam in one dimension. By changing the angle of incidence you can affect how much the beam width is changed. Confirm this experimentally as well.

By placing two prisms one right after the other you can selectively affect the two different axes of your laser beam pretty independently. Such a prism pair is also ideal to form a round(er) beam from an originally strongly elliptical beam, simply by affecting one axis more than the other. You can even arrange the two prisms such that the resulting beam is only displaced (i.e. the prism pair doesn't introduce an additional angle in your beam propagation), but still propagates in the same direction, and the beam width is still affected in exactly the way you want it.

Play with this a little (but be careful not to send your beam all over the place!). Mount the first prism safely and place a second prism right behind it. Again change the angle of incidence and confirm that this prism pair allows you to affect both axes of the laser beam independently.

10 Diffraction gratings

In this section we will briefly observe the interference pattern on a screen behind a single and two multiple slits. Most of you have probably done the Intro Physics II lab in which you measure the distance between two consecutive minima and extract the wavelength of the laser from this measurement. If you have never studied the single or double slit, please let your instructor know and they can provide you with more information. Here, we will not derive any expressions that describe the interference pattern. Please check your introductory physics textbook for this derivation, or ask your instructor. Instead, we will quickly move on to diffraction gratings and their properties, since you will use such a grating in `MODULE 3 - INTERMEDIATE and ADVANCED` to tune the wavelength of a diode laser, and in `MODULE 4 - INTERMEDIATE` to build a small spectrometer. The *Mightex* CCD spectrometer you used earlier also contains diffraction gratings. Remove all lenses and place them back in their boxes. Then store them in the lens cabinet. Also remove the beam expander and store it.

*** Review your knowledge of the interference pattern when you send a beam through a single slit, a double slit, and through multiple slits, and sketch it.**

Summarize the overall trend as you go from a single to a double and lastly to multiple slits. Comment on the width of the central maximum as well as on the widths of all other maxima and minima.

A diffraction grating is essentially the continuation of this sequence: It contains a large number of slits, on the order of several hundreds to thousands per mm. Diffraction gratings come in two versions: As transmission grating and as reflection grating. `'DEMO 11a'` is a transmission grating, while `'DEMO 11b'`, and `'DEMO 11c'` are reflective gratings. [Please make sure to put on gloves and do not touch the shiny colorful surface of the grating. Unlike mirrors and lenses that are often coated with protective layers that allows you to gently clean them as you learned earlier in this module, these gratings have no coating and cannot be cleaned. So, any fingerprint on them will destroy them.] A simple CD or DVD is another example of a reflective grating (you can find it in 'Module 1 demos' box).

How to pick a diffraction grating:

There are a few different types of diffraction gratings, all optimized for specific applications.

1. **Ruled reflective diffraction gratings:** These gratings are designed such that the first-order diffracted peak is maximized for a specific wavelength. The surface of this type of grating consists of a series of steps that are angled with respect to the surface normal. Each step reflects a little bit of the incident light, and because the steps are angled, the resulting reflected beams interfere with one another. By picking the height of the steps and the angle carefully, you can design a grating that produces constructive interference at the design wavelength. For more information, go to Thorlab's website (`www.thorlabs.com`), then go to 'Optics' → 'Optical Elements' → 'Gratings' → 'Visible Ruled Reflective Gratings'. There, click on the 'Grating Tutorial' tab.
2. **Holographic reflective diffraction gratings:** Holographic gratings use a similar principle, but they are designed with slightly different applications in mind. While the diffraction efficiency is typically a little bit lower than with ruled reflective gratings, these gratings reduce the amount of scattered light from the surface, making them ideal for applications that require low levels of stray light and do not need high diffraction efficiencies.
3. **Echelle reflective diffraction gratings:** These gratings are optimized for applications that use higher diffraction orders. In fact, the `'DEMO 11'` grating is such an Echelle grating.
4. **Transmission diffraction gratings:** Unlike the other three types of gratings, transmission gratings create the constructive interference in the first (or higher) order when the beam passes through the grating. They are transparent, and the grating structure is typically created by scratching or etching a repetitive, parallel pattern onto the substrate.

Hold the DEMO gratings (`'DEMO 11'` is an Echelle grating, `'DEMO 11a'` is a transmission grating, and `'DEMO 11b'` and `'DEMO 11c'` are reflective gratings with a different number of lines per mm) and the CD/DVD under a white-light source such as the ceiling lights or the flashlight in your phone. You can also use one of the white LEDs (connect it to a 9 V battery).

Describe what you see.

Now focus on the Echelle grating.

Compare the separation between the different wavelengths in the first order and in the second (or higher) order. Can you see a trend?

Keep these observations in mind. You will use such a reflective diffraction grating in `MODULE 3 - INTERMEDIATE and ADVANCED` to direct one specific wavelength of this 'wavelength comb' back into a laser diode, which increases the amount of stimulated emission at that wavelength and "encourages" the laser to lase at that particular wavelength. Gently rotating the diffraction grating and thus changing the wavelength that is sent back into the laser diode is a great way to tune a laser diode over several MHz. In `MODULE 4 - INTERMEDIATE` you will use a diffraction grating to build a small spectrometer, similar to the *Mightex*.

11 Polarization optics:

As you hopefully remember, light is an electro-magnetic wave, which means that it consists of an oscillating electric and magnetic field that are perpendicular to one another and to the direction of propagation of the wave. The direction of oscillation of the *electric* field vector is called the **polarization** of the electro-magnetic wave. For example, vertically linearly polarized light has an electric field vector that oscillates up and down as the wave propagates forward, while the electric field vector of horizontally linearly polarized light oscillates left to right. Of course, linear polarization can be under any angle. The electric field vector can also change orientation as the wave propagates, leading to elliptically polarized light (or the special and very important case of circular polarization).

You can change the polarization state of an electro-magnetic wave by using birefringent materials that have different refractive indexes depending on the direction of propagation through the material. The most common ones are listed in the 'How to' box below.

How to change the polarization of light:

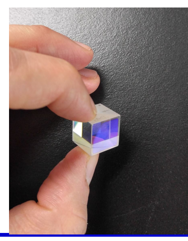
- **Polarizers** are thin transparent foils containing long chains of molecules that are all aligned parallel to one another. When an electro-magnetic wave is incident with the polarization *along* these chains, the electric field accelerates the electrons in the molecules, forcing them to move along the chains. This requires energy, of course, and the electro-magnetic wave is attenuated; the polarizer blocks this polarization. On the other hand, when the polarization is perpendicular to the chains, the electric field cannot accelerate the electrons, and such a wave passes through the polarizer with minimal absorption. Thus, polarizers selectively absorb all but one polarization.
- **Polarizing beamsplitters, PBS,** come in various designs. Here, we will use PBS *cubes*, PBSCs. They consist of two halves shaped like a pyramid that are glued together at the base with a transparent cement. On top of the cement layer is a thin dieletric beamsplitter coating that allows horizontally ('P') polarized light to pass, while it reflects vertically ('S') polarized light. Thus, if a beam with linear polarization under some angle enters the PBSC, its vertical component is reflected while the horizontal component is transmitted. You can find the two components just as you would find the x- and y-component of a vector.
- **Wave plates** are thin transparent disks made from a birefringent material, a material that has two different refractive indices: One is along the 'optics (=fast) axis', while all directions perpendicular to this axis have a different index. Thus, since the refractive index affects the speed of light, a wave traveling along the axis travels faster than a wave traveling perpendicular to it. By carefully designing the orientation of the fast axis of the wave plate with respect to the direction of incidence, as well as the thickness of the plate, you can create half-wave plates that rotate linear polarization, and quarter-wave plates that turn linearly polarized light into elliptically polarized light (more below).

How to mount polarization optics:

- **Polarizers and wave plates:** Put on gloves before you touch the polarizers, and hold them on the outer edge (don't touch the middle). Find the mark on the edge of the polarizer. This mark indicates the direction of the molecule chains. Similarly, the mark on the edge of a wave plate indicates the direction of the fast axis. Carefully place the polarizer or wave plate into the inner ring of the nested 1" lens holder (shown on the bottom-left of the left photo below) and secure it with the retainer ring, similar to how you would secure a lens in a lens mount. Make sure that the mark on the polarizer/wave plate aligns with the zero on the ring (as best as you can manage, see middle photo below). Then place the inner ring into the outer ring (top-left of the left photo below) and tighten the thumb screw so that it doesn't fall out (right photo). Attach the outer ring to a post and place the post into a post holder with base. Please also watch the `VIDEO` called `HOW TO MOUNT A HALF-WAVE PLATE` on our website.



- **Polarizing beamsplitter cubes:** Put on gloves and gently hold the PBSC on the two rough surfaces (top and bottom, left photo below). Place the cube onto a platform mount and lower the lever until it touches the top of the cube. Push down on the lever and lock the set screw. Attach a post and place it into a post holder (right photo below). Please also watch the `VIDEO` called `HOW TO MOUNT A PBSC` on our website.




Two of our HeNe lasers are linearly polarized; the third one has a random polarization. Your goal is to identify this random polarization laser and to determine the direction of polarization of the other two lasers *using only the polarizers.* .

Discuss with your group members how you want to do this, and briefly summarize the battle plan (including a sketch). Then put on your goggles and perform the experiment

Now repeat this task *using only the polarizing beamsplitter cube.* Again, discuss the battle plan with your group members, briefly summarize it (include a sketch), and then perform the experiment.

You may have found that your results from these two measurements agree reasonably well, but probably not perfectly, with one another. That's because in order for the PBSC to work well, you need to align it more carefully. Here's how you do it (please also watch the `VIDEO` called `HOW TO ALIGN A PBSC` on our website):

How to align a polarizing beamsplitter cube:

- Make sure that the cube is level with the surface of the optics table. Adjust the thumb screws on the platform mount if it isn't.
- Place the PBSC into the laser beam such that the beam hits the cube under a right angle.
- Place a half-wave plate in front of the PBSC and rotate the wave plate until the *reflected* beam is minimized.
- Now gently rotate the PBSC about an axis perpendicular to the table, such that the angle of incidence of the laser beam is no longer exactly $0°$. While rotating, observe the power of the reflected beam. There should be an angle close to the $0°$ angle of incidence you started with for which the reflected power is *clearly* minimized.
- Lock down the PBSC at this angle.
- Lastly, confirm that by rotating the half-wave plate you see a minimum in the reflected beam with a corresponding maximum in the transmitted beam, and by rotating it further you can find an angle at which the reflected beam is maximized and the transmitted beam is minimized.

You already saw that by rotating the half-wave plate you can adjust the amount of power in the two 'ports' of the PBSC. We'll do this more systematically now by recording the power of the transmitted and reflected beams as a function of the angle of the half-wave plate. Rotate the wave plate the full $360°$ in steps of $\Delta°$. Discuss with your group whether Δ should be 1, 5, 10, or larger to get meaningful data. Record your data set in a table in the box on the next page and sketch it.

Then replace the half-wave plate with the quarter-wave plate and repeat the previous experiment. Again, record your data in table form in the box on the next page and sketch it.

Compare the two measurements and explain them as good as you can. We will revisit PBSCs, and half-/quarter-wave plates in `MODULE 3 - ADVANCED.`

Half-wave plate data:

Quarter-wave plate data:

Comparison and discussion:

Lastly, go back to Thorlab's website and open the page on mirrors again. In section 8.1, where you picked the best mirror for a given laser wavelength, we told to focus on the 'unpolarized' curve. Now that you know a little bit more about polarization, look at all three curves and compare them.

What can you conclude? How should you polarize your laser beam in order to minimize losses and is this answer generally true for all types of metal mirrors?

And to wrap this up, we want to show you a neat way of how you can detect linear polarization *with your naked eye*. This phenomenon is called 'Haydinger's Brush'. Take out your cell phone and open a blank white screen. The app 'Bright Screen Light' works beautifully for this task. Look at the screen (turn off the other lights in the room) and rotate the cell phone by about 90 degrees right, and then back again to the upright position. Repeat this multiple times. This will make it easier to see the effect. It is a subtle one, but once you see it you know that you see it.

And that's it! You made it successfully through the first module and are now qualified to perform the more advanced modules. Please leave us any comments, suggestions, or concerns in the box below, so that we can optimize this module for future student generations. Thanks!