OPTIX Module 3 – Basic

Interference of two Laser Beams

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1 Objectives:

In this module you will learn more about

- Helium-Neon lasers;
- the Michelson Interferometer;
- interference and its dependence on polarization.

This module is part of our Modern Physics curriculum and prepares you for `MODULE 3 - INTERMEDIATE and ADVANCED` on diode lasers and absorption spectroscopy of rubidium, respectively, as well as for research on ultracold atoms and molecules in the Kleinert lab. It should take about 3 hours to complete.

Use this manual as you work through the module to keep track of your notes and thoughts. In addition, you may have to add a few printouts or refer to data tables or additional notes in your lab notebook. I'd encourage you to create a Jupyter Notebook for your calculations and plots. Make sure to add all your printouts to the folder in which you keep this manual. Lastly, note that this lab has no formal lab report. Instead, you will turn in and be graded on your notes in 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.

In addition, 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:

You can find most of the equipment for this module in the box labeled 'HeNe Optics' that is located in one of the cabinets in the OPTIX lab. Standard equipment that is used for multiple modules will be located in other cabinets in the OPTIX lab. Please feel free to also ask your instructor for help. You will need:

- one helium-neon laser cell with driver and mount,
- a power supply to drive this laser,
- two commercial helium-neon lasers (note: ask your instructor to show you the linearly polarized ones!)
- several mirrors, polarizing beam splitters, half-wave plates.

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

In this module you will investigate the phenomenon of interference in more detail. In particular, you will compare two situations: a) you will overlap light from two *different* lasers, and b) you will overlap light from one laser that has been split into two beams. In addition, you will study how the polarization of the light affects the interference pattern.

Thoroughly review the *Laser Safety Material* before coming to lab; there will be a brief test about laser safety before you will be allowed to start this module. Make sure to **always wear your laser goggles unless your instructor tells you that it is safe to take them off**. Besides general laser safety you don't need to know anything about lasers; we will use them as a tool to study physical phenomena. You will learn more about how they work later in this semester in Modern Physics and in `MODULE 3 - INTERMEDIATE and ADVANCED`.

Make sure to read through the *whole* manual before coming into the OPTIX lab, and mark everything that you find difficult to understand. In addition, **work through all the boxes marked with a *. Be prepared to discuss your completed work with the group and your instructor before starting the lab. This counts as your pre-lab.** 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.

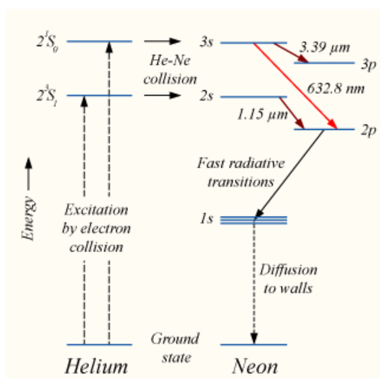
If you damage anything, please tell your instructor *immediately*. While we of course try to avoid damaging the equipment since it is rather pricey, especially in this lab, accidents can happen. Please don't try to cover up any damage; that only makes life harder for us as we try to figure out why something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

*** Lastly, write down everything related to lasers and interference that you remember from a previous classes in the box below. Any relations, sketches, key words that pop into your head. If you can connect them in a meaningful way, even better! And now - have fun in the lab!**

5 Helium-Neon lasers:

In this module you will use the same helium-neon lasers ("HeNe" lasers) you already used in MODULE 1 - BASIC (Optics Basics - I) or INTERMEDIATE. Your instructor will also show you a more bare-bones HeNe tube laser (and please watch the VIDEO called HOW TO SET UP THE HENE LASER TUBES on our website before coming to lab).

The helium-neon laser is a gas laser, which means that the active medium in which the lasing occurs consists of a gas. There are also lasers that use solids, liquids, or semiconductors instead of a gas. Even though you may not yet have learned about stimulated emission, which is an essential part of a laser, you probably have some understanding of basic atoms and atomic energy levels. In a very basic picture, you can imagine the protons and neutrons located in the center (nucleus) of the atom, with the electrons on "orbits" around the nucleus. These orbits have very specific and discrete energies. Without providing the electrons with additional energy from the outside, they will be located in the lowest possible energy level. For example, in a single-electron atom, the electron resides in the *ground state*. By providing this electron with energy, e.g. through an applied electric field or photons of just the right frequency, it can be promoted into one of many *excited states*. In the case of the helium-neon laser, a high-voltage excites and accelerates electrons, which then collide with and excite the electrons in the helium atoms to the first excited state. When such an excited state helium atom collides with a ground state neon atom, the energy can be transferred from the helium to the neon atom, thus creating an excited state neon atom. But this excited state neon atom cannot stay excited forever; it will release the energy in the form of a photon of wavelength 632.8 nm. That's exactly the color you see when you turn on a helium-neon laser. You may wonder why this has to be so complicated. Why do we have to excited helium and transfer that excitation to neon to get laser light out? Why not excite neon directly? The reason has to do with what's known as *population inversion*, and the fact that it is not that easy to achieve. In fact, you can show that it can never be achieved in a simple two-level atom (you need at least three atomic energy levels that participate in this process). A helium-neon laser is an example of a four-level system that is optimized to achieve population inversion, leading to highly efficient laser emission. You will understand this better toward the end of your Modern semester, and you don't need a deep understanding of the underlying physics to complete this module successfully. The figure below (taken from Wikipedia) shows you the atomic level structure of a helium-neon laser.



6 Laser interference with one laser:

In Intro Physics II you learned that light can be described as a wave, and you saw experimental evidence of this when we studied single and double slit interference. In this part of the module we will revisit interference, but instead of using slits, we will split the laser beam into two beams and then recombine these two beams. This is similar to the *Michelson interferometer* that you also discussed in Intro Physics II.

*** Before coming to lab, briefly review the Michelson interferometers.**

To split the laser beam into two beams, we will use *polarization* dependent equipment: half-wave plates and polarizing beamsplitter cubes. Light waves are electro-magnetic wave which consist 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. This is a bit arbitrary (you could also have chosen the direction of the magnetic field vector), but it is convention. 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 when the tip of the electric field vector moves along a circle).

You can change the polarization state of an electro-magnetic wave by using **birefringent** materials that have different refractive indices 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 polymers 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 polymer chain, 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 refractive 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 changing 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, or quarter-wave plates that turn linearly polarized light into elliptically polarized light (more below).

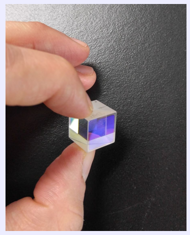
Mounting them is pretty straight forward:

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`.

How to mount polarization optics, cont'd:

- **Polarizing beamsplitter cubes:** Put on gloves and gently hold the PBSC on the two rough surfaces (top and bottom, left photo below). Don't touch the polished surfaces! 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). If you can't find a platform mount (or if there aren't enough), you can also use double-sided sticky tape to temporarily attach the cube directly to a post. Please note, though, that this is a *temporary* solution and should *not* be used when you design permanent optics. Also watch the `VIDEO` called `HOW TO MOUNT A PBSC`.



For this project, you have to align the PBSC carefully. It's not quite as easy as inserting it more or less perpendicular to the beam. The following box and the `VIDEO` called `HOW TO ALIGN A PBSC` explain how to do it.

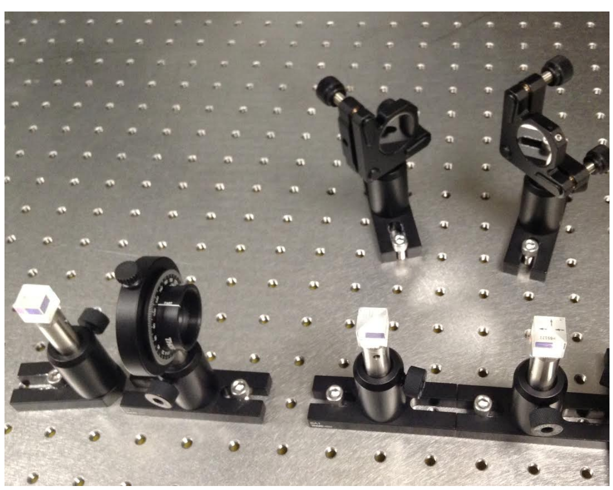
How to align a polarizing beamsplitter cube:

- 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.

We are now ready to set up the experiment. Place one of the HeNe lasers onto the optics table and turn it on. Place a half-wave plate into the path of the laser beam such that the laser hits it in the middle of the glass window and perpendicularly. You can find the half-wave plates and polarizing beamsplitter cubes in the box labeled "HeNe lasers and optics", which is in one of the upper cabinets in the OPTIX lab. A half-wave plate can rotate the orientation of the polarization vector of the laser light. For example, you can rotate the initial polarization vector of your laser from vertical to horizontal and back, just by rotating the half-wave plate. Next, place a polarizing beamsplitter cube into the beam (so following a photon from the laser, that photon would first hit the half-wave plate and then the polarizing beamsplitter cube) and align it correctly following the steps outlined above. **Please check with your instructor after you have aligned your first PBSC.**

Rotate the half-wave plate in steps of 10° over a total of 180° and record the reflected and the transmitted power as a function of the angle of the half-wave plate. There is more space on the next page. Use a correctly labeled table to hold your data, and graph your results either by sketching them in this manual or by quickly plotting them in a Jupyter notebook. Don't waste too much time on this! Note: It is easiest to record the data for, say, the transmitted beam first, and then move the power meter and record the data for the reflected beam. That way you don't have to switch back and forth repeatedly. In your analysis, discuss your results. Hint: Think about the horizontal and vertical polarization components and what happens to them as you rotate the overall polarization vector.

Now adjust the half-wave plate such that you get about 50% of the power into the reflected and 50% into the transmitted beam, thus splitting the laser power in half. This polarizing beamsplitter cube is shown on the **bottom-right** of the following figure. We will now slowly set up the rest of the optics shown in that figure, i.e. the two mirrors near the top, and the two additional PBSCs and another half-wave plate to the left of your first PBSC. Please also watch the `VIDEO` called `HOW TO SET UP THE INTERFEROMETER` on our website.



Place another polarizing beamsplitter cube directly behind the first one as shown in the figure. Carefully look at the orientation of the diagonal of the cube: You want the first cube to reflect the beam up, and the second cube to reflect the beam down, so the first diagonal must be oriented top-left to bottom-right, the second one from bottom-left to top-right (refer to the photo). Then place two mirrors as shown and move the reflected beam such that it and the transmitted beam are perfectly overlapped after the second polarizing beamsplitter cube. To do this, roughly align the reflected beam such that it is reflected by the second PBSC. Then place a piece of paper directly behind the second polarizing beamsplitter cube and use the first mirror to overlap the two dots (from the transmitted and the reflected beam) on that paper. Remove the paper and use the *second* mirror to overlap the two dots on a wall. Insert the paper again, use the first mirror to overlap the dots. Remove it, use the second mirror to overlap the dots on the wall, etc. Iterate until the two dots are overlapped on both the paper and the wall. This procedure is called "walking the beam" and ensures that the two laser beams, the one that is transmitted through both cubes and the one that is reflected by both cubes, overlap everywhere in space. Referring back to the photo, you should now have completed the right half of the setup, with two additional elements, another PBSC and a half-wave plate, still missing at this point. **Check with your instructor when you have completed this step.**

*** Would you expect there to be an intereference pattern on the wall? To answer this question, think about what the "detour" that the reflected beam experiences as it is redirected by the two mirrors does to the reflected beam. Thus, is there a difference between the transmitted and the reflected beam? And what happens when the two beams (the two waves!) meet up again after the last PBSC?**

Without your goggles, observe the overlapped spots on the wall.

Do you see an interference pattern?

This experimental result may surprise you and is quite possibly the exact opposite of what you predicted in the above box! Don't erase your first answer, though! You probably thought about all the right things, you just neglected to take one important additional component into account: the polarizations of the two overlapping beams.

As you learned in the 'How to' boxes above, a PBSC separates the horizontal and vertical polarization components of an incident beam. The reflected beam is vertically polarized while the transmitted beam is horizontally polarized.

Using this information, describe what happens when the transmitted and the reflected beam reach the second PBSC, and explain what their polarization state is after they have passed through this PBSC. Thus, what can you say about the *relative* polarizations of the two beams when they hit the wall?

To experimentally test if polarization (or more precisely, the relative polarization states of the two overlapped beams) is really the main issue here, we will insert *another* half-wave plate and a third PBSC after the second cube as shown in the setup figure on page 6. After you have inserted these two components, block the reflected beam and rotate the newly inserted half-wave plate while observing the power in the transmitted and the reflected port of the third PBSC.

Find and record the angles of maximum and minimum transmission, as well as maximum and minimum reflection for this transmitted beam.

Unblock the reflected beam and block the transmitted beam.

Again, find and record the angles of maximum and minimum transmission, as well as maximum and minimum reflection for this reflected beam.

Unblock both beams and double check that they are still nicely overlapped. Observe the pattern on the wall while slowly rotating the newly inserted half-wave plate. You should find a range of angles for which you can see a clear interference pattern consisting of bright and dark stripes. Adjust the half-wave plate until the contrast between the bright and dark stripes is best.

Record the angle of the half-wave plate when the contrast is maximized:

$\theta_{max} =$

Then block the transmitted beam and measure the power of the reflected beam in the transmitted and reflected port of the third PBSC for this angle:

$P_{R,trans} =$ $P_{R,refl} =$

Block the reflected and unblock the transmitted beam and again measure the transmitted and reflected power:

$P_{T,trans} =$ $P_{T,refl} =$

How do the two transmitted/reflected powers compare? How does the angle θ_{max} compare to the range of angles you found in the previous box? Explain these observations!

Note that both laser beams are now emerging as *transmitted* beams from the third PBSC.

What can you conclude about their relative polarization? Thus, what can you conclude about the importance of the polarization of both beams when it comes to interference?

7 Laser interference with two different lasers:

We will now see what happens when we replace one of the laser beams with a separate laser. To do this, take a second HeNe laser and place it under a 90° angle with respect to the first laser so that it points towards the first mirror. Remove the first PBSC, the one that split the incoming laser beam in the two beams you used in the previous experiment, but leave the rest of the equipment in place. This way, you again have two laser beams, but this time they come from two different lasers: The first one is the transmitted beam of your original laser, the second one is the new laser that bounces off the two mirrors and meets the first laser on the remaining (second) PBSC.

Repeat the alignment procedure outlined above to ensure that the two beams are nicely overlapped after they have met on the remaining PBSC. It helps to first ensure that the two laser beams are at about the same height. After you have nicely overlapped the beams, observe the pattern on the wall.

Do you see an interference pattern?

This observation probably makes sense to you, because the two lasers are not in sync. While photons in a *single* laser are all synchronized (this has to do with the stimulated emission of a laser that you'll learn about later in this semester), the photons in two *different* lasers are not. You can picture the photons in a single laser as members of a well-trained marching band, all marching in sync. And while this statement is true for the photons within *each* of the two lasers, the two different lasers play to different tunes, and the two marching bands are not synchronized at all. That way, when they meet, things get a little bit chaotic and we don't see an orderly interference pattern. The technical term for this is "coherence" (or rather, lack thereof).

Briefly review the three interference experiments you performed today. Compare and contrast them and clearly work out the conditions that are required to see an interference pattern. Note that you can do this after class if you are running out of time.

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!