Physical Optics

Pre-Lab: An Introduction to Light

A Bit of History

In 1704, Sir Isaac Newton postulated in *Opticks* that light was made up of tiny particles that behaved just like any other massive object, from planets to protons. He hypothesized that light is observed to travel in a straight line because it moves at such a high speed, just like a Nolan Ryan fastball appears to travel in a straight line instead of a parabola. The particle model of light also explained many other aspects of light's behavior, such as reflection and refraction (both of which describe the ways in which light bends when in contact with a surface). Newton was the number one name in physics for more than two centuries, so when he espoused a theory, people believed it. It also didn't hurt that the particle model readily explained commonly observed phenomena. Because of this, the particle model of light dominated until Thomas Young, who also helped decipher the Rosetta Stone (boy, was he an overachiever!), performed his double slit experiment in 1801. This experiment conclusively demonstrated the diffraction and interference of light, which are properties that can only be explained by a wave model of light.

Particle or Wave?

Modern quantum theory holds that light has both wave-like and particle-like properties. The act of making an observation forces the light to display its particle or its wave properties (in quantum mechanics, this is called collapsing the wave function). Whether light will display its wave-like or particle-like properties depends on the experimental design, the wavelength of the light, and on the length-scale of the object used to observe the light (e.g., the slit separation in Young's double slit experiment). When the wavelength of light is large, the slit separation tends to be smaller than or comparable to the wavelength of light and its wave nature dominates. As the wavelength of light decreases, the particle nature of light begins to dominate. In the experiment today, all of the slits through which you will observe light are small enough that you can treat light purely as a wave. Physical phenomena that can be described by only the wave nature of light are commonly referred to as physical optics. It is more physically realistic than describing light as a ray, as is done in geometric optics. For additional information on waves, diffraction, interference, and polarization, see: Appendices B and D, Moore Chapters Q1 – Q5, or Young & Freedman Chapters 33, 35, and 36.

The Structure of This Lab

This lab will deal with two major topics of physical optics: polarization and interference. The Pre-Lab will focus on polarization while the time in the laboratory will be spent investigating interference.

An Introduction to Polarization

This series of Pre-Lab exercises will introduce you to polarization with the ultimate goal of gaining a basic understanding of polarizing sunglasses and 3D movies. Appendix D gives an introduction to some of the history and essential math of polarization. Check it out!

You can use the polarizer you received in lab last week to help you answer some of the questions. If you did not receive a polarizer, you can stop by the TA Office (Crow 207) or the lab manager's office (Crow 307) and pick one up.

Equipment

- Polarizer (see the paragraph above)
- Sunglasses

The Story

One day you decide to give your little brother a call to catch up and to tell him how much you're learning in your introductory physics class. But all he wants to talk about is his current favorite movie, *Mutant Zombie Piranhas from Outer Space in 3D*, which he avows is infinitely more thrilling than science could possibly be. You beg to differ, and seeing a way to reel him in, you mention that modern 3D movies are only possible because of science – namely, polarization. Just as you had hoped, he takes the bait and asks you to explain this. Pleased to have caught his interest and in the number of fish-related puns you were able to utilize, you tell your brother that he'll need to start with the basics if he wants to understand how movies work.

> **Do This:** Take the polarizer you received in lab last time (polarizers are also available in the hallway across from Crow 307 and in the Crow 207, the TA office) and look at a variety of objects, both indoors and outdoors, as you ***rotate*** the polarizer. That's when the magic of the polarizer happens! Examples of objects you might look at include, but are not limited to, your computer screen, your phone screen, a light bulb, the table, your lunch, the sun (indirectly, of course!), the sky, etc. Be creative!
>
> PL1. List at least three objects that appear different when you look at them through a polarizer and three that don't seem to significantly change. Make sure it's clear in your response which is which.
>
> PL2. Describe the effects a polarizer has on the objects that appear to change. What happens when you rotate the polarizer while looking at these types of objects?
>
> PL3. Many sunglasses are polarized. Based on what you've already discovered about how polarizers change the way certain types of objects look, determine whether or not your sunglasses are polarized. (Or if you don't have sunglasses, find a friend who does.) Clearly explain your procedure, observations, and analysis.

Do This: Use the Pre-Lab link on the lab website to watch an introduction to the science of polarization in the context of 3D movies. You will answer several questions related to the video.

PL4. In your own words, describe the analogy the video makes between polarizers, waves, and the cardboard sheet with vertical slits cut into it.

PL5. How do polarized glasses make sure each eye only sees the image intended for it, effectively doing the same thing as closing one eye, without all the squinting?

Read This: Modern 3D movies are projected using circularly polarized light. However, there is no fundamental reason why 3D movies couldn't use linear polarization – the projectors would just need to produce vertically and horizontally polarized light and you would wear the corresponding glasses. However, there is one major practical issue.

PL6. Consider a 3D movie projected using linearly polarized light. What would happen to the movie if you were to tilt your head while wearing linearly polarized glasses? Explain the problem and why circularly polarized light is a solution.

Read This: Now your brother is hooked (another fish pun!) and wants to know more about where polarization is used. Sunglasses and 3D movies are two of the most common modern uses of polarization, but there are many more out there. Polarization can be a useful tool, even without understanding the science of what's happening. This is true for people (polarization wasn't discovered until 1809 – see Appendix D for the interesting tale), plants, and animals.

PL7. Do a bit of independent research to find an example of how polarization is used (not simply where it exists: where it is *used*), either in nature or by people pre-1809. Describe the phenomenon in a few sentences, just like you would to a little brother.

Read This: Just like visible light, x-rays can be polarized. Professors Krawczynski and Beilicke are collaborators in *X-Caliber*, an experiment looking at the polarization of x-rays emitted from various exotic sources. Check out the lab website for links to details.

Part I: The Digital Revolution

The Story

You are home for Spring Break and your technologically-challenged grandparents are trying to put one of those new-fangled DVDs into their old CD player. After you introduce them to the DVD player, they ask you why the heck there have to be so many types of discs out there?! What is the advantage of one over another? Your grandparents may not know about Twitter and iPods, but they do remember their college physics. You decide to begin their enlightenment on the myriad of advantages Blu-ray and DVD discs have over CDs by examining the amount of data each disc can hold. Fortuitously lying around their house is the equipment to build an interference experiment (they *really* enjoyed college physics labs!).

Equipment

- Laser apparatus with two test leads
- Power supply
- Screen (ruler mounted on ring stand)
- Slide of double slits in holder
- CD (label removed, greenish tint)
- DVD (label removed, purplish tint)
- Transparent vinyl record
- Meter stick

The Basics

The first thing you do is explain the basics about compact discs (CDs), digital versatile discs (also called digital video discs, or DVDs), and Blu-ray discs. All three discs are made through similar processes. The discs are made of polycarbonate (a type of plastic), which are then coated in aluminum and a smooth layer of acrylic, and finally covered by a label. Data are etched onto the bottom surface of the polycarbonate by a laser that creates a series of bumps of equal height, but varying length (Figure 1). The laser in your home CD/DVD/Blu-ray player reflects off the bumps on the disc as it spins and the electronics in your CD/DVD/Blu-ray player then read this reflected light and translate it into a movie or a song. The details of exactly how this happens are complicated and well beyond the scope of your explanation. From the top of the disc (the label side), these bumps appear to be pits, which is what people commonly call them. For a CD, the pits are 500 nm wide, 125 nm high, and a minimum of 830 nm long. The pits on a DVD are 320 nm wide, 120 nm high, and a minimum of 400 nm long. The pits on Blu-ray discs are even smaller. DVDs and Blu-ray discs can have a second polycarbonate layer that also stores data; this is how dual-layer DVDs and Blu-rays are created.

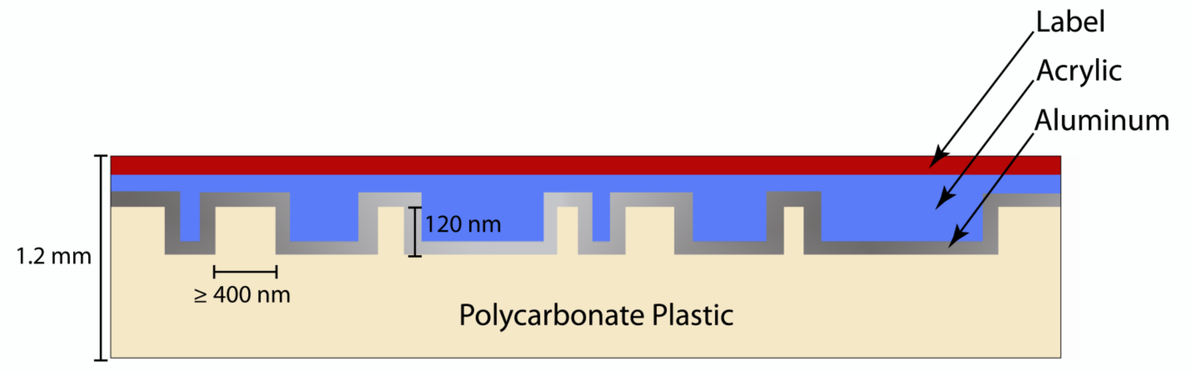

Figure 1: Layers of a DVD (drawing is not to scale)

The pits are laid out on the disc in a spiral pattern that starts at the center of the disc and curves outward toward the edge. The spiral is etched as tightly as possible, and the distance between adjacent rings, known as the "track pitch" (see Figure 2), depends upon a number of variables and is different for each type of disc.

An interesting but not terribly germane point in this discussion of pits and discs is that scientists at Northwestern University recently used the pit patterns from Blu-ray movies to imprint solar cells. It turns out that the pits help solar cells absorb and store more light, just like pits help discs store data. As it happens, any movie will do, so *Mutant Zombie Piranhas from Outer Space in 3D* works just as well as *Citizen Kane*. For more information, check out the In-Lab links.

The adjacent rings in the tight spiral can function like the slits in Young's experiment. Any arrangement with a very large number of slits is referred to as a *diffraction grating*. A diffraction grating can separate white light into individual wavelengths. This is why diffraction gratings, CDs, DVDs, and Blu-ray discs all appear to have a rainbow of color on their surface. With this knowledge in hand, you are ready to prove to your grandparents that they can ditch all those bulky CDs and put Barry Manilow's entire repertoire on one convenient disc.

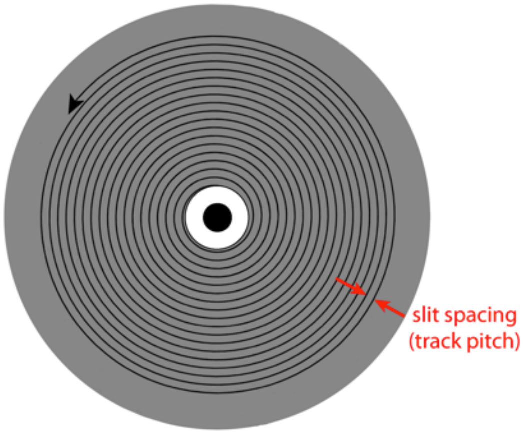

Figure 2: Data are etched by a laser in a spiral pattern on the CD, DVD, or Blu-ray disc. The spacing between adjacent rings in the spiral corresponds to the slit separation (d) in Figure 6 in Appendix B. This spacing, called the track pitch, is a constant for each disc type (drawing is not to scale).

1. Preliminary Measurements - Determining the Wavelength of a Laser

You realize that while your grandparents conveniently have a laser set up on the dining room table, they don't know its wavelength. "But the laser is red!" your grandparents protest, eager to get to the data storage experimental punch line. You politely remind them that "red" is not a wavelength; "red" light includes the range of wavelengths from about 620 – 700 nm. You realize that before you can learn anything about the track pitch of a CD or DVD, you will need to find the wavelength using a slit of known spacing. Being safety conscious, you issue the following warning to anyone within eyeshot of a laser.

☠Warning: The low-power laser beam used in these experiments will not cause permanent damage to your retina, but it can produce annoying after-images that may persist for several minutes or longer. DO NOT allow the beam to shine (either directly or by bouncing off a shiny surface) into anyone's eyes.

> **Do This:** Here's how to operate the laser. First, make sure that the laser is NOT connected to the power supply. Then turn on the power supply. Set the voltage to 3.0 V. The laser can be damaged by greater voltages. The laser can also be damaged if you connect it to the power supply backwards. Keeping that in mind, connect the laser to the power supply such that the red terminal of the laser is connected to the red terminal of the power supply. That leaves the black terminal of the laser to be connected to the black (blue) terminal of the power supply. Alert your TA if the laser doesn't work.
>
> **Checkpoint 1.1:** Look at the slide, which contains four double slit configurations of different separations (and see Appendix C). Which configuration will be most useful to find the wavelength of the laser?
>
> **Do This:** Use the slit configuration you decided on in Checkpoint 1.1 to produce an interference pattern on the screen (the ruler mounted on a stand).
>
> **Checkpoint 1.2:** Record the distance between the slide and the screen (D) and the location (y) of the first order maximum ($n = 1$). Then use your measurements to calculate the wavelength of the laser. Discuss the validity of any approximations you make.
>
> **Checkpoint 1.3:** Now record the location (y) of the maximum with the highest order (n) that you can clearly identify. (By "clearly identify" we mean you have **absolutely no doubt** about the value of n to which the maximum corresponds.) Don't forget to record the value for n, as well. Then use your measurements to calculate the wavelength of the laser. Justify any approximations that you make.
>
> **Checkpoint 1.4:** Estimate the uncertainty in the distances that you recorded in Checkpoint 1.2 and Checkpoint 1.3.
>
> **Read This:** Knowing the uncertainty in those distances is nice, but what we'd really like to know is the uncertainty in the wavelength that you calculated. Since the wavelength is calculated using the values n, d, y, and D, the uncertainty in the wavelength will be a function of those

values and their uncertainties. It can be shown that for small angles like the ones you are dealing with, the uncertainty in the wavelength, $\Delta\lambda$, is approximately given by

$$\Delta\lambda = \lambda\sqrt{\left(\frac{\Delta y}{y}\right)^2 + \left(\frac{\Delta d}{d}\right)^2 + \left(\frac{\Delta D}{D}\right)^2 + \left(\frac{\Delta n}{n}\right)^2} \qquad \text{Eq. 1}$$

where λ is the best guess value that you have calculated. In the next few Checkpoints you will simplify this equation and then use it to assess your experimental wavelength values.

Checkpoint 1.5: What is the uncertainty in n? (Keep in mind the phrase "absolutely no doubt" from Checkpoint 1.3.) Rewrite Eq. 1 taking this into account.

Checkpoint 1.6: The slide is a precision piece of lab equipment, especially when compared to a meter stick. The uncertainty in the slit separation (Δd) is small enough for us to ignore. Simplify the equation you came up with in Checkpoint 1.5 by ignoring any uncertainty contributed by the slide.

Checkpoint 1.7: The equation that you wrote down in Checkpoint 1.6 is still unnecessarily complicated. As often happens, one of the sources of uncertainty (that is, one of the terms under the radical) is much larger than the other terms. Discuss which term is, by far, the largest. Then ignore the smaller term and simplify the expression for the uncertainty in the wavelength.

Checkpoint 1.8: Using the equation you found in Checkpoint 1.7, write the wavelength that you found in Checkpoint 1.2 using the form $\lambda \pm \Delta\lambda$.

Checkpoint 1.9: Using the equation you found in Checkpoint 1.7, write the wavelength that you found in Checkpoint 1.3 using the form $\lambda \pm \Delta\lambda$.

Checkpoint 1.10: Discuss your two values for the wavelength of the laser. Address each of the following:

a) Which best guess value do you trust more? Why?
b) Are the two values consistent with each other?
c) Are the two values red? If the better value is not red then you should consult your TA.

Read This: This exercise in uncertainty analysis really highlights the concepts of *absolute uncertainty* vs. *fractional uncertainty*. The absolute uncertainty in y is simply Δy. Most often the word "absolute" is left out. The fractional uncertainty in y is defined as $\frac{\Delta y}{y}$. Sometimes this is reported as a percentage.

Read This: You should have found that the wavelength you calculated using the larger y value had a smaller uncertainty than the wavelength that you calculated using the smaller y value. Both of those y values have the same *absolute* uncertainty since they were measured with the same ruler. However, the larger y value had a smaller *fractional* uncertainty. By reducing the fractional uncertainty of a length that you used to calculate λ, you were able to get a more precise value for λ. In most cases, if a measured value has a high fractional uncertainty then anything you calculate using that measured value will have a large fractional uncertainty as well.

Checkpoint 1.11: Show that you understand the definition of fractional uncertainty by calculating the fractional uncertainty for the y values you recorded in Checkpoint 1.2 and Checkpoint 1.3. Then compare these values to the fractional uncertainty in the value you recorded for D and discuss.

S1

Synthesis Question 1 (25 Points): You have been directed to perform two experiments to determine the wavelength of the laser. Sort through your notes and write a report about the experiment that gave you the better results. A complete response will include the following:

- A diagram of the experimental setup that helps define the variables in equations that you use. (Make this nice, because you might refer to it in your responses to other questions in this lab.)
- A visualization (sketch, plot, photo, etc.) of the interference pattern that shows what distances you measured
- Your procedure
- A calculation of the best-guess wavelength
- A calculation of the uncertainty in the wavelength(You do not need to derive the formula for the uncertainty in your response, but show how you use it.)
- A brief discussion about what steps you took to minimize the uncertainty in the wavelength
- A plausibility statement regarding your results

2. Determining Track Pitch of the CD

You now have all the tools in place to determine the track pitch of the three discs that you have been given.

Do This: Replace the slide of slits with the CD and use it as a diffraction grating to produce an interference pattern on the screen. (The CD has a greenish tint.) Note that despite having *many* more slits, the diffraction grating will produce maxima in the same location as predicted by Young's two slit experiment. See Appendix B for an explanation of why.

Checkpoint 2.1: Measure all important distances and record them in your notes.

Read This: Recall that the track pitch of a disc refers to the spacing between adjacent grooves on the spiral that holds the information. Please see Figure 2 for clarification.

Checkpoint 2.2: Use your data to calculate the track pitch (d) of the CD **without using** the small angle approximation.

Checkpoint 2.3: Use your data to calculate the track pitch (d) of the CD again, this time **using** the small angle approximation. Then discuss the validity of the small angle approximation in this situation.

Read This: It's typically not a good idea to use the small angle approximation with diffraction gratings. The slits are so close together that the angles are almost always going to be too big. You can usually get away with the small angle approximation if you're working with a double slit. As a rule of thumb, if the interference maxima all appear to be equally spaced, then the small angle approximation is valid. On the other hand, like with the CD, if the maxima are **not** equally spaced, the small angle approximation is **not** valid.

Checkpoint 2.4: Which order maximum did you use to calculate the track pitch? Explain why you chose one order over another.

Checkpoint 2.5: Do some math to show why you couldn't find an $n = 3$ maximum.

Checkpoint 2.6: Use your computer to find a quoted value for the track pitch of a CD. Please record your source in addition to the value.

Checkpoint 2.7: Figure 3 in Appendix A shows a CD imaged by a scanning electron microscope (SEM). Use the figure to determine the track pitch of a CD.

S2

Synthesis Question 2 (25 Points): Sort through your notes and write a report showing how you determined the track pitch of the CD and how you assessed the plausibility of your result. A complete response will include the following:

- A visualization (sketch, plot, photo, etc.) of the interference pattern that shows what distances you measured
- Your procedure
- A calculation of the track pitch of the CD
- A quantitative comparison between your experimental value and a value you found online
- A quantitative comparison between your experimental value and a value you found using Figure 3 in Appendix A

3. Determining Track Pitch of the DVD

The DVD is the disc that is tinted purple.

S3

Synthesis Question 3 (25 Points): Perform an experiment to determine the track pitch of the DVD and assess the plausibility of your result. A complete response will include the following:

- A visualization (sketch, plot, photo, etc.) of the interference pattern that shows what distances you measured
- Your procedure
- A calculation of the track pitch of the DVD
- A quantitative comparison between your experimental value and a value you found online
- A quantitative comparison between your experimental value and a value you found using Figure 4 in Appendix A
- A comparison between the track pitch of the DVD and the track pitch of the CD along with a plausibility statement regarding the comparison

4. Determining Track Pitch of the Record

The record is the large, clear disc.

S4

Synthesis Question 4 (25 Points): Perform an experiment to determine the track pitch of the record and assess the plausibility of your result. A complete response will include the following:

- A visualization (sketch, plot, photo, etc.) of the interference pattern that shows what distances you measured
- Your procedure
- A calculation of the track pitch of the record
- A quantitative comparison between your experimental value and a value you found using Figure 5 in Appendix A
- A plausibility statement that takes into account the track pitch of the CD and DVD.
- A plausibility statement that takes into account the limits of human vision.

CURRENT RESEARCH

Read This: Hopefully your experiments have shown that taking a very close look at interference patterns can give you very precise information about the geometry of a material. In fact, scientists use the same basic ideas that you have used in this lab to analyze crystal structures, examine welds, and even try to improve the international standard for the kilogram! (You might want to take a second look at the Scientific American article you read as part of the Pre-Lab to the Measurement lab last semester.) The Laboratory for Materials Physics Research at Wash U uses electron diffraction, x-ray diffraction, and neutron diffraction to study the structure of various substances. See the lab website for links to details.

Appendix A: Close-ups of the Discs

This appendix contains three images created using a Scanning Electron Microscope or SEM. All three of the SEM images were produced by Chris Supranowitz at the University of Rochester and can be found on his website: http://www.optics.rochester.edu/workgroups/cml/opt307/spr05/chris/

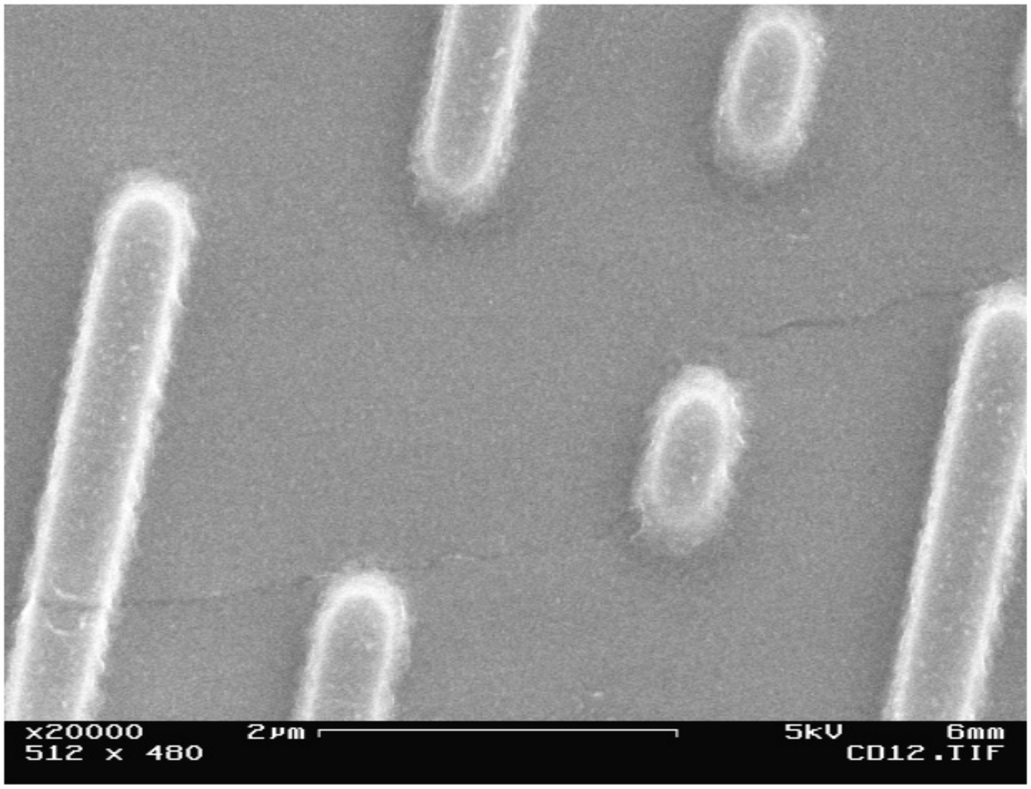

Figure 3: SEM image of a CD. The lighter features are pits. Note the scale.

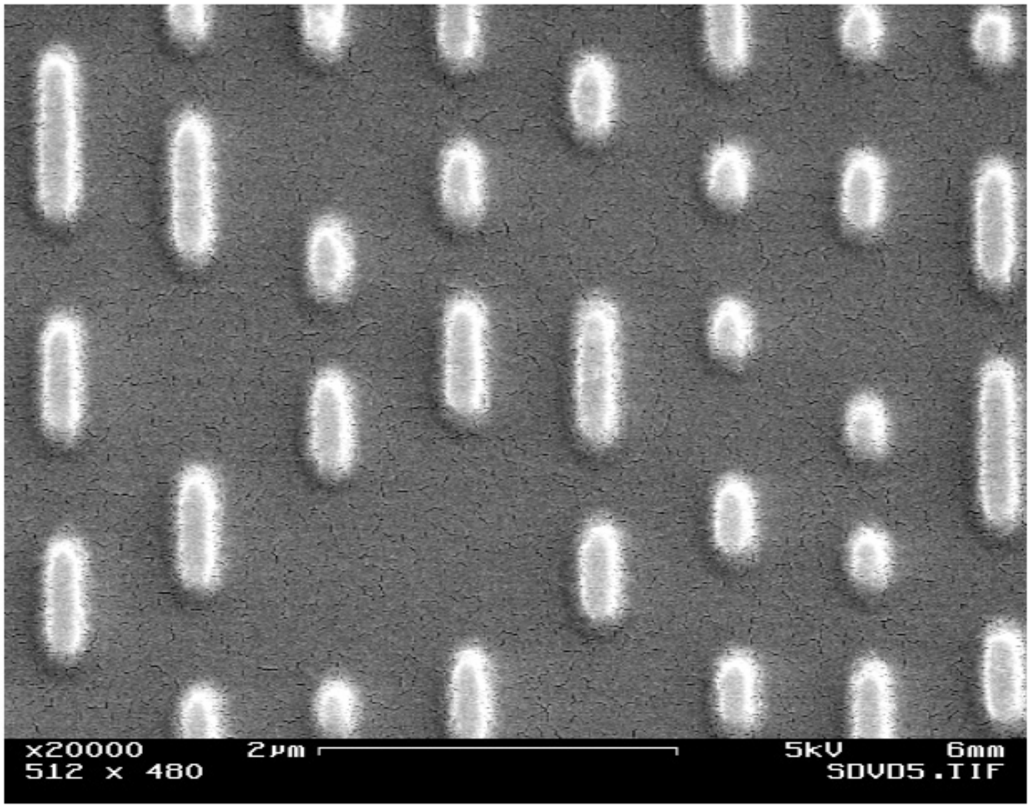

Figure 4: SEM image of a DVD. The lighter features are pits. Note the scale.

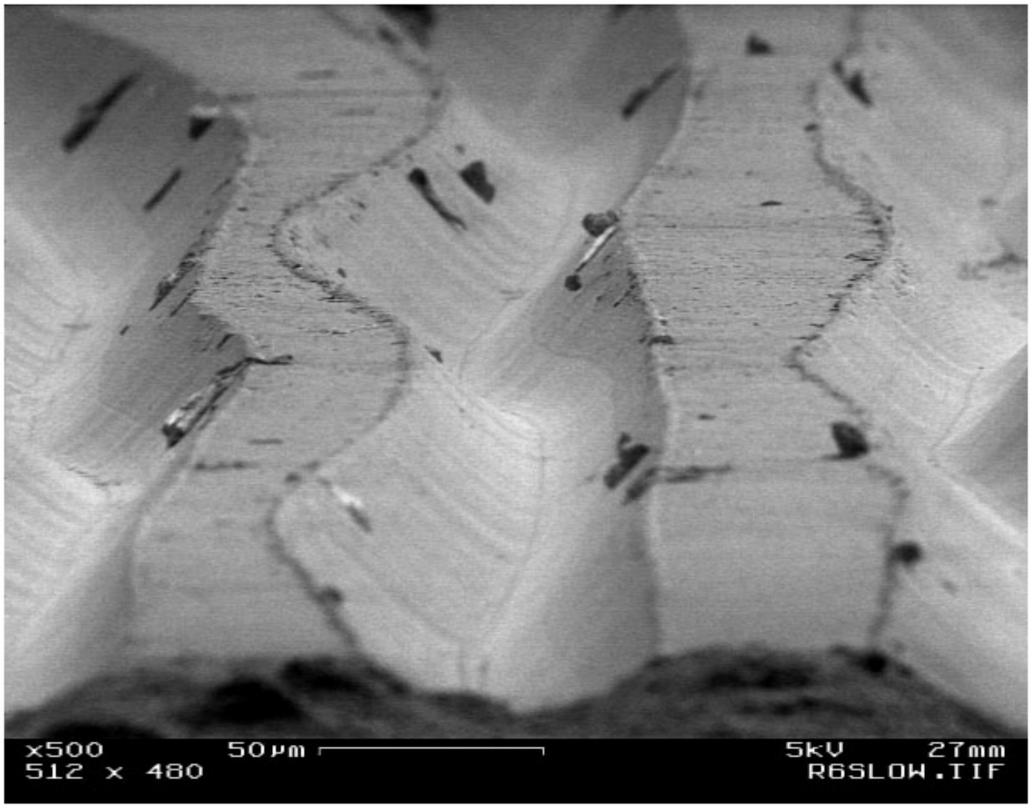

Figure 5: SEM image of a vinyl record. Note the scale.

Appendix B: Interference and Diffraction

Huygens's Principle states that given a wave front at some initial time, subsequent wavefronts can be constructed at some later time by treating each point on the initial wavefront as the source of a circular wave that spreads out with a fixed amplitude and speed. Diffraction occurs when a wave bends around an obstacle it encounters, such as a slit, and subsequently spreads out into a circular wave according to Huygen's Principle. This will create points of constructive and destructive interference, resulting in a diffraction pattern.

When there are multiple slits, each wave not only constructively and destructively interferes with itself, as in diffraction, but also with the wavefronts from the other slits. The resulting sequence of bright and dark spots is called an interference pattern. This is true for all types of waves, including sound, water, and light waves.

The location *P* of the n^{th} point of *constructive* interference is governed by the following equation:

$$d \sin \theta = n\lambda$$

The location *P* of the n^{th} *maxima*, as measured from the central axis is given by the following equation:

$$y = D\tan \theta$$

Where: n is an integer describing the maxima of interest, located on a screen at point *P*; θ is the angle between the central axis ($n = 0$) and *P*; y is the distance between the central axis and *P*; D is the distance between the slit and the screen; λ is the wavelength of light; and d is the center-to-center distance between the slits (Figure 6).

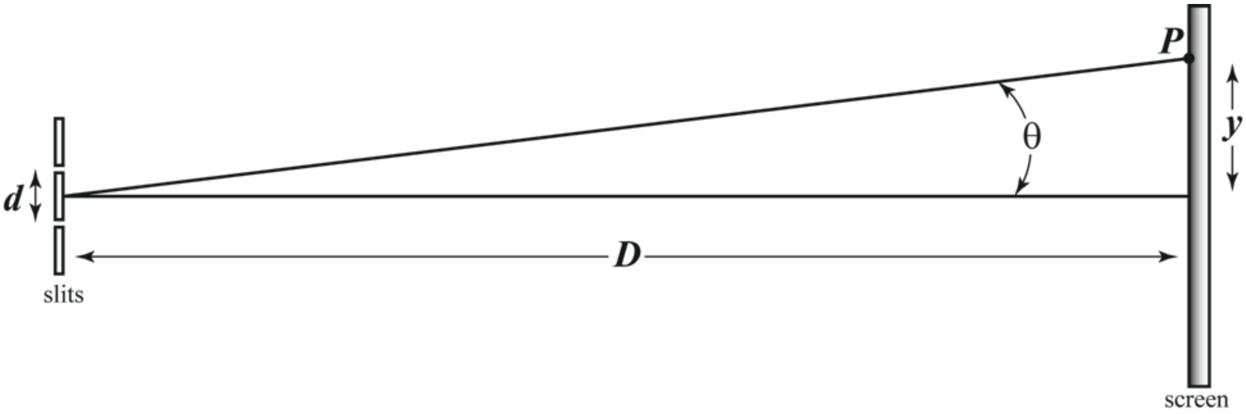

Figure 6: Young's double slit experiment

Diffraction gratings, like the ones used in this lab, can have many slits, all with the same separation d. You have to add in the extra waves at *P* from each of these extra slits, taking proper account of their phase shifts. Each new slit will add in a wave shifted in phase by δ from the one before. This makes for significantly more complicated interactions. However, the condition for constructive interference of the light from all the slits is unchanged – the interference maxima remain at the same angles as in the case of two slits. The main difference is that the maxima become narrower and narrower as the number of slits increases.

For N slits, the angular width of a maximum (ϕ) is given by:

$$d \sin \phi = \frac{\lambda}{N}$$

Narrow maxima (small ϕ) are just what the doctor ordered to distinguish two almost equal wavelengths. This is why diffraction gratings with $N \geq 10{,}000$ are so useful in studying atomic and molecular spectra.

Appendix C: Double Slit Slide

All four configurations are double slits, but the separation between the two slits differs for each pattern. Use the center-to-center slit separation (printed below each pattern, in mm) as the quantity d in the formula in Appendix B. Each individual slit is 0.15 mm wide.

Our slits are very exotic, imported all the way from Germany (Guten Tag!). This means that the numbers are written in the European style, so commas are used in place of what you are used to seeing as a decimal place. Therefore, the first pair of slits has a separation of 0.25 mm, etc.

Figure 7: Slide containing four double slit patterns

Appendix D: Polarization and Malus' Law

A Bit of History

In 1808, physicist Etienne-Louis Malus was gazing through a piece of Icelandic spar, a very clear type of calcite crystal, at the sunset reflecting off the windows of the Luxemburg Palace in Paris. He noticed some very strange things happening when he rotated the crystal, a property that would eventually be understood as double refraction (sometimes called double diffraction instead). Malus' observations on that evening prompted him to explore the phenomenon further, leading to the first scientific explanation of polarization. For his troubles, Malus received the very nifty honor of being one of 72 French scientists, engineers, and mathematicians to have their names inscribed on the Eiffel tower (other names you might recognize from this semester are Ampère, Fourier, and Coulomb).

Malus' Law

At its most basic level, Malus' Law mathematically describes how polarizers affect the light that passes through them. When unpolarized light passes through a polarizer, only components of the electric field vector parallel to the axis of polarization will get through. This is true for each polarizer, whether there is one, two, or twenty.

Let's take the relatively simple case of two polarizers. If we want to know how much light from the first polarizer will make it through the second, we can just look at what's going on with the electric field vectors. As Figure 8 shows, only components of the electric field parallel to the axis of polarization (and therefore parallel to E_2 – see Figure 8) will be able to pass through the second polarizer. However, remember that the electric field that already passed through the first polarizer (E_1) and is now incident on the second polarizer is composed of two component vectors: one parallel to E_2 and one perpendicular to E_2. These components are labeled $E_{\parallel}$ and $E_{\perp}$, respectively, in Figure 8.

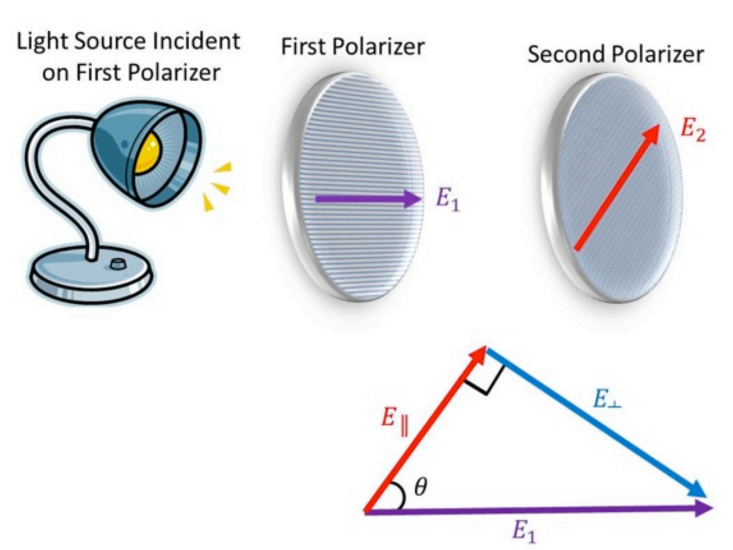

Figure 8: Components of the electric field that will pass through polarizers oriented at an angle θ with respect to one another.

Therefore, the fraction of the electric field (E) that passes through both the first and second polarizer is equal to:

$$E = E_1 \cos\theta$$

Since the intensity of light is proportional to the square of the electric field, the total intensity of light that (I) that passes through both the first and second polarizer is equal to:

$$I = E_1^2 \cos^2\theta = I_1 \cos^2\theta$$

Finally, if we generalize this equation so that the light that passes through the first polarizer and is incident on the second polarizer has the subscript i we have Malus' Law:

$$I = I_i^2 \cos^2\theta$$

In the case of more than two polarizers, Malus' Law can be used for each set of polarizers. Just apply the law separately to *each pair* of polarizers! For the case of three polarizers in a row, you would therefore need to apply Malus' law to the first and middle polarizer together and determine the intensity of light that emerges from the middle polarizer. Then apply Malus' law again with the light that emerged from the middle polarizer as the incident light on the third polarizer.