

# Chapter 4 Polarization

## 4.1 Introduction

Polarization generally just means “orientation.” It comes from the Greek word *polos*, for the axis of a spinning globe. Wave polarization occurs for *vector* fields. For light (electromagnetic waves) the vectors are the electric and magnetic fields, and the light’s polarization direction is by convention along the direction of the electric field. Generally you should expect fields to have three vector components, *e.g.* (x,y,z), but light waves only have two non-vanishing components: the two that are perpendicular to the direction of the wave. In this experiment, we will be concerned with the polarization of light. The most elegant tests of quantum mechanics have been performed by measuring correlations of the polarization of photons from atomic transitions. This is beyond the scope of these experiments, but it's good to keep in mind that some of nature's thornier problems are lurking in the corners.

Electromagnetic waves are the solutions of Maxwell’s equations in a vacuum:

$$\begin{aligned}
 \nabla \cdot \mathbf{E} &= 0 \\
 \nabla \cdot \mathbf{B} &= 0 \\
 \nabla \times \mathbf{E} &= -\frac{\partial \mathbf{B}}{\partial t} \\
 \nabla \times \mathbf{B} &= \epsilon_0 \mu_0 \frac{\partial \mathbf{E}}{\partial t}
 \end{aligned} \tag{4.1}$$

In order to satisfy all four equations, the waves must have the  $\mathbf{E}$  and  $\mathbf{B}$  fields transverse to the propagation direction. Thus, if the wave is traveling along the positive  $z$ -axis, the electric field can be parallel to the  $+x$ -axis and  $\mathbf{B}$ -field parallel to  $+y$ . Half a cycle later,  $\mathbf{E}$  and  $\mathbf{B}$  are parallel to  $-x$  and  $-y$ . Since the fields oscillate back and forth several hundred trillion times per second, we don’t usually know their *sense* (*i.e.*  $+x$  vs.  $-x$ ). Polarization of light therefore only refers to *direction* (*e.g.*,  $x$ ), not sense.

If the light propagates in the opposite direction, along  $-z$ , then the  $\mathbf{E}$  and  $\mathbf{B}$  fields are instead respectively parallel to  $+y$  and  $+x$ . The direction the light travels is determined by the direction of the *vector cross product*  $\mathbf{E} \times \mathbf{B}$ .

In the following sections, we will try to explain polarization phenomena in terms of both mathematical expressions for wave amplitudes and symmetry. When applicable, symmetry arguments are the simplest and usually easiest to understand. However, as situations become more complex, it is useful to have a mathematical description robust enough to cover any conceivable physical arrangement. The first tool we need is a way of describing plane waves traveling along the  $z$ -axis of Cartesian space, with wavelength  $\lambda$  and frequency  $f$ :

$$\mathbf{E}(z, t) = \mathbf{E}_0 \cos(kz - \omega t) \tag{4.2}$$

where  $k = 2\pi / \lambda$  and  $\omega = 2\pi f$ . In this expression, ‘cos’ could be equally well replaced by ‘sin’. What is important is the relative sign of the  $z$  and  $t$  arguments. If  $z = ct = (\omega/k)t$ , as time advances, the phase of the wave remains constant. This is a plane wave traveling in the positive  $z$ -direction at velocity  $c$ . Conversely,  $\mathbf{E}(z,t) = \mathbf{E}_0 \cos(kz + \omega t)$  describes a wave traveling in the negative  $z$ -direction. This could equally well be described by  $\mathbf{E}(z,t) = \mathbf{E}_0 \cos(-kz - \omega t)$ . The only criterion is that the sign of the  $z$  and  $t$  terms are the same for this backward propagation direction.

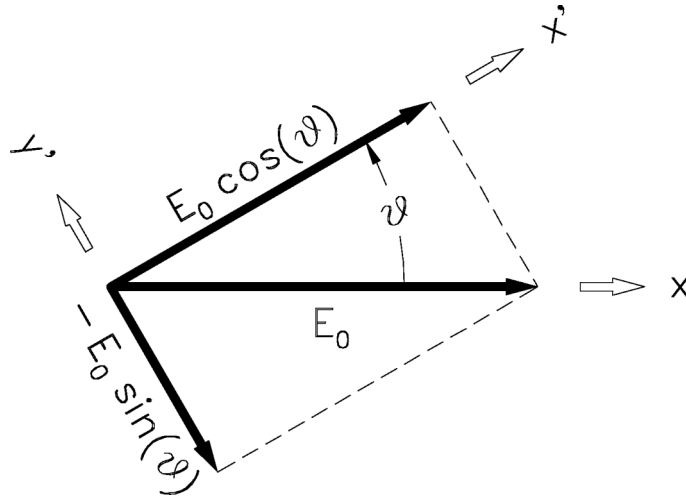


Figure 4.1: A wave polarized along the  $x$ -direction can equally well be represented by the coherent sum of amplitudes along the  $\hat{x}'$  and  $\hat{y}'$  axes.

In what follows, we will ignore the magnetic field,  $\mathbf{B}$  since its value can be immediately inferred from the functional form for  $\mathbf{E}$  by applying Maxwell’s equations. Thus, it adds no additional degree of freedom to the range of allowable solutions.

The following experiments include a “take-home” kit of polarized materials as well as a series of exercises that must be done in class because of the additional equipment requirements. The kit should contain the following items:

1. Three linear polarizers (grayish)
2. 1/2-wave plate (transparent)
3. 1/4-wave plate (transparent)
4. Right-circular polarizer (grayish)
5. Left-circular polarizer (grayish)
6. Glass microscope slide; plastic box; piece of aluminum foil

## 7. Red, green, and blue plastic filters

As you go through the various parts of this experiment, take careful notes in your lab notebook and label each part clearly by section number.

## 4.2 Linear Polarization

A beam linearly polarized along the  $x$ -axis and traveling in the positive  $z$ -direction can be represented by:

$$\mathbf{E}(z, t) = E_0 \hat{\mathbf{x}} \cos(kz - \omega t) \quad (4.3)$$

where  $\hat{\mathbf{x}}$  is the unit vector along the  $x$ -axis. Of course, the choice of coordinate system is completely arbitrary. If we have a second coordinate system rotated by an angle  $\theta$ , about the  $z$ -direction (see Figure 4.1), we would represent the same beam by:

$$\mathbf{E}'(z, t) = E_0 \cos\theta \cos(kz - \omega t) \hat{\mathbf{x}}' - E_0 \sin\theta \cos(kz - \omega t) \hat{\mathbf{y}}' \quad (4.4)$$

Although in this primed reference frame, there are both  $x$ - and  $y$ -components, the wave is still plane polarized because the space and time dependence of the two components are identical. This relationship can obviously be inverted – if you know the two components of the amplitude in the primed frame, you can find the rotation angle of the polarization direction. The function of a linear polarizer is to transmit only the amplitude parallel to the axis of the polarizer. If this direction is parallel to the  $x$ -axis, only the  $x$ -component of the field will survive and the  $y$ -component will be removed. For incident light with random polarization, only half will survive. This is why linear polarizers always look gray under normal illumination (for example, Polaroid sunglasses).

Now suppose we superimpose a second linear polarizer at right angles to the first so light is only transmitted with  $\mathbf{E}$  parallel to  $\hat{\mathbf{y}}$ . The joint transmission of the two will be zero because the output of the first will be completely attenuated by the second. We can relax this condition and ask what happens for intermediate angles between polarizers. Suppose that the allowed polarization direction of the second polarizer is set at angle  $\theta$  to the first. In the preferred frame of the second polarizer, the  $\mathbf{E}$  field is given by Equation 4.4. Only the component parallel to  $\hat{\mathbf{x}}'$  will be transmitted by this second filter and so the amplitude through the pair will be proportional to  $\cos\theta$ . For an *ideal* polarizer the light intensity is proportional to the square of the amplitude, so that the dependence of intensity with polarizer angle is:

$$I(\theta) = I_0 \cos^2 \theta \quad (4.5)$$

This is called Malus's law.

- Verify Malus's law using an incandescent light source and the two 5 cm diameter linear polarizers. Mount one in a 2" lens holder and the other in the rotary mount. Use the photodiode and Hewlett-Packard DVM to measure the light intensity in the same way as

performed in Experiment 2. Put a green interference filter in the light beam just in front of the photodiode. The polarizers are most efficient in this part of the spectrum. Use a lamp voltage of 10 V, and a spacing  $\sim 30$  cm between the light source and the detector. Keep the polarizers at least 5 cm from the bulb (or they will be ruined!).

For the following, use the two linear polarizers from your kit after you have identified them as explained in the next section

- With the two polarizers crossed so that minimum light is transmitted, interpose a third linear polarizer at  $45^\circ$  in the middle. What happens? Explain why.
- Under the same conditions as above, insert various transparent objects such as plastic boxes, eyeglasses, microscope slides with transparent tape, *etc.* What do you find?

### 4.3 Polarization by Reflection

Your polarized light kit has five grayish filters, of which three are linear polarizers and two are circular polarizers. In this part of the experiment, you should separate the two different kinds of polarizers and mark the transmission axes on the linear polarizers.

- You need a table with a lamp or a window near the far end as shown in Figure 4.2. Put a magazine or a book with a shiny cover on the table and put the microscope slide from the kit on top. Look at an angle such that the reflection of the light makes it difficult or impossible to read the print in the magazine and/or to read the print below the glass microscope slide.

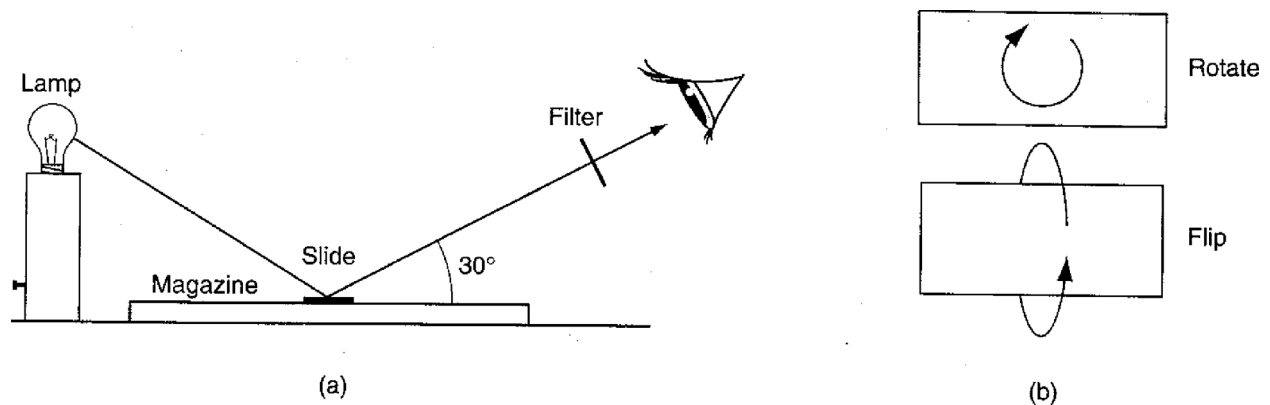


Figure 4.2: Glare allows determination of polarization transmission axis

- Now try each of the grayish filters in front of your eye. Rotate each filter as shown in Figure 4.2b to see if you can find a position of the filter in which it will best reduce the glare. You can then move the magazine and your head until the glare reduction with the filter is most dramatic. Use that setup from now on. When you rotate the filter through  $90^\circ$  the glare should become very bad again. Now flip the filter over so that you look through the opposite side. Rotate the filter after flipping it over and try to find out if it

makes any difference whether you look through the filter from one side or the other. For the linear polarizers, flipping should have no effect.

- For circular polarizers, the behavior is distinctly different. Now you should be able to separate your five filters into a group of three linear polarizers and two circular polarizers. List in your notes all the features you found that distinguish the two groups.
- Hold each of the three linear polarizers in front of your eye so that it best reduces the glare and then mark with a vertical line on small circular paper labels that you can attach to each filter. Now you should be able to pick up each filter with the line in a vertical position and get the best glare reduction. Your line marks the filter transmission axis.
- Now that you are a beginning expert, gather a variety of objects of different materials; put them in place of the magazine and record what you observe with a linear polarizer. Examples: a piece of paper on which you have written a few words with a soft (No. 2) pencil, a shiny metal surface, the plastic box of your kit, and other objects. Which objects shown polarization effects? The ability of polarizing filters to preferentially block reflected light from water and other smooth surfaces makes them valuable for sunglasses; they reduce glare far better than the unpolarized variety.

## 4.4 Polarization by Scattering

On a clear day, if you look at the blue sky through a polarizer, you can turn the polarizer so that the sky looks darker and white clouds stand out beautifully. Photographers use polarizing filters for this purpose. The light from the sky is partially polarized, but you must look in the right direction for a maximum effect (the "midway belt" in Figure 4.3). The blue color of the sky is due to the fact that the short wavelengths (blue) of the light from the sun are scattered more effectively by the atmosphere than the longer wavelengths (red).

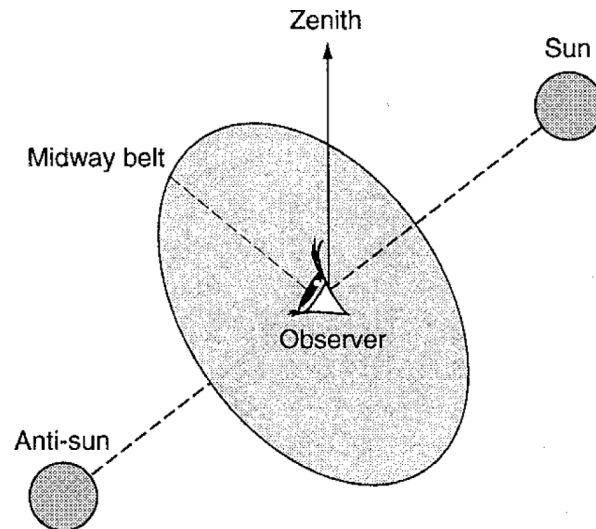


Figure 4.3 Diagram for observing the polarization of sky light

In the following experiment, let light from an incandescent lamp pass through water with a few drops of milk to scatter the light. If you look at the water through a linear polarizer, you can see that the light intensity varies as you turn the polarizer. You can use this to find the direction of polarization. The incident light is unpolarized, but the light scattered out of the liquid is obviously partially polarized. The scattered light is produced when electrons in the liquid are caused to oscillate transverse to the beam direction by the E-field of the incident light. At a  $90^\circ$  scattering angle, these vibrations can only have components perpendicular to the scattering plane or along the scattered direction. Since the E-field must vanish along the propagation direction, the latter contribution must vanish. Verify that the polarization direction is consistent with this explanation. The scattered light is only partially polarized because part of the light is scattered more than once. In such multiple scattering, the light does not remain in one plane. The line of sight is no longer always perpendicular to the direction of propagation and multiply scattered light is less polarized.

- Look through a linear polarizer at the milky water through which you shine light. Turn the polarizer and find the direction of polarization. Put a linear polarizer between the lamp and the water and rotate it. You can thus verify which polarization direction is responsible for the scattered light.

## 4.5 Optical Activity

If you want to do this experiment at home you should mix approximately one part of clear *Karo* corn syrup and one part of water in a glass, or better, a square bottle. However, we also have square bottles with *Karo*, *etc.* available for use in the labs.

- Mount a linear polarizer behind the bottle and another linear polarizer in front as shown in Figure 4.4. Use the rotary mount for one of these so you can measure angles carefully. Let light shine through both filters and through the solution; turn the filter nearest you

and record what you see. The optical rotation depends on wavelength; use the color filters in your kit to determine the rotation for red, green, and blue light.

- Without the solution between the polarizers or with plain water, extinction would occur when the polarizers are crossed. You will notice that this is no longer true with the corn syrup inserted between. The solution rotates the direction of polarization, *i.e.*, it is optically active. You should find out whether you now need to rotate the nearer filter clockwise or counter-clockwise to get extinction. Record this angle and other experimental results in your notes. (Note: To verify that the rotation is, say  $20^\circ$  clockwise rather than  $160^\circ$  CCW, you should figure out a way to vary the thickness of solution).

Fruit sugar (fructose or levulose) and turpentine rotate in the opposite direction (how about honey?)

Note: The rotation is due to an asymmetry in the corn syrup molecules which can be right-handed or left-handed. Only living organisms produce this handedness - this is one of the mysteries of life. Almost all amino acids produced by living organisms here on Earth have a left-handed optical activity. Amino acids found in certain meteorites are equal mixtures of right- and left-handed molecules. This has been used as evidence of their extraterrestrial origin. Thus if you are a health worker and someday take a blood sample from someone and it exhibits right-handed optical activity, use caution. You may be dealing with an alien.

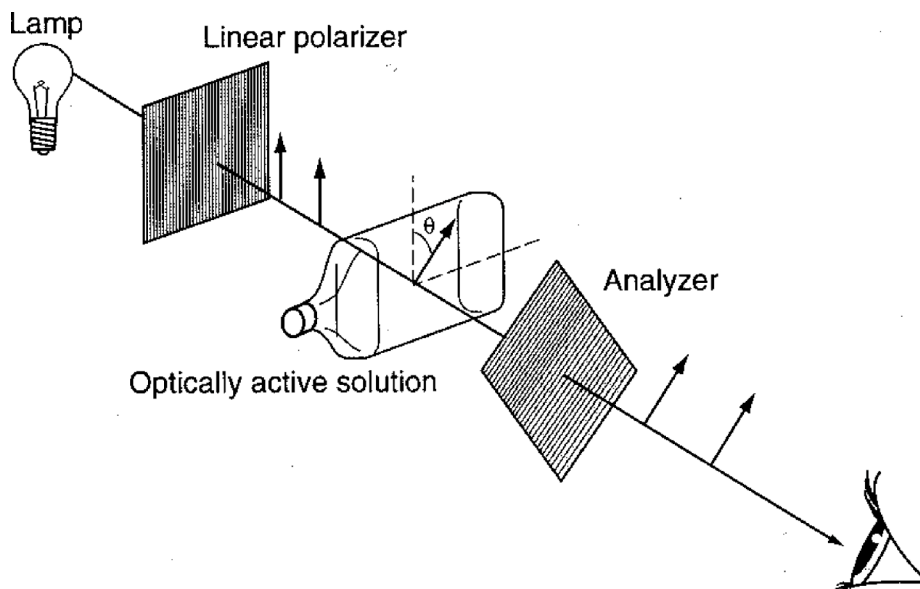


Figure 4.4 A corn syrup solution rotates the direction of polarization

It has been found that the odor associated with chemically indistinguishable molecules is correlated with optical activity. For example, one molecule whose solution causes a right-handed rotation of polarized light has an orange odor. Its mirror image structurally causes left-handed rotation and has a lemon odor. Strange but true.

Chemists use devices called *polarimeters* to examine and measure the optical activity of chemical compounds. This can be used to identify compounds, *etc.* Also, since optical activity changes when a *magnetic field* is applied (the so-called Faraday effect), optical and radio astronomers study polarized light and radio waves to deduce the magnetic fields in stars and galaxies.

## 4.6 Circular Polarization and Reflection

Your “take-home” kit has two grayish circular polarizers. You should already have identified and marked the 3 linear polarizers, and therefore the two that remain must be circular polarizers (if nobody goofed!). Here is one way to check:

- Put one circular polarizer on top of a shiny (not a painted) metal surface (mirror, knife blade, scissors, a dime). Flip it over. When you have the correct side up the dime will look very dark. Mark the up side with a C. Do this with both circular polarizers (Prof. Jens Zorn of the University of Michigan says that he has won much money betting other physicists at meetings that they will not be able to explain why the metal looks dark through the filter). Compare these results with what you observe by doing the same experiment with a single linear polarizer.
- If you put the two circular polarizers back to back with the two sides marked C on the outside of the sandwich, very little light will go through no matter how you rotate the filters – if you indeed received one L and one R (left and right) filter as you should have.

To create circularly polarized light, we must be able to somehow control the relative phase of the  $x$ - and  $y$ -components. Fortunately there are various materials that are slightly anisotropic. Because of their atomic structure, linearly polarized light will travel at different velocities along two transverse axes. By choosing the appropriate thickness, one can make a  $1/4$ -wave plate (sometimes called a  $\lambda/4$ -plate), that introduces a  $90^\circ$  phase shift; or a  $1/2$ -wave plate (sometimes called a  $\lambda/2$ -plate) that introduces a  $180^\circ$  phase shift. Assume we start out with light polarized along a  $45^\circ$  line to the  $x$ -axis:

$$\mathbf{E}_0(z, t) = \frac{E_0}{\sqrt{2}} \cos(kz - \omega t) \hat{\mathbf{x}} + \frac{E_0}{\sqrt{2}} \cos(kz - \omega t) \hat{\mathbf{y}} \quad (4.6)$$

After traversing a quarter-wave plate aligned with its crystal axes parallel to  $\hat{\mathbf{x}}$  and  $\hat{\mathbf{y}}$ , a net phase shift of  $90^\circ$  will occur so that the wave can now be represented by:

$$\begin{aligned} \mathbf{E}_0(z, t) &= \frac{E_0}{\sqrt{2}} \cos(kz - \omega t) \hat{\mathbf{x}} + \frac{E_0}{\sqrt{2}} \cos(kz - \omega t \mp 90^\circ) \hat{\mathbf{y}} \\ &= \frac{E_0}{\sqrt{2}} \cos(kz - \omega t) \hat{\mathbf{x}} \pm \frac{E_0}{\sqrt{2}} \sin(kz - \omega t) \hat{\mathbf{y}} \end{aligned} \quad (4.7)$$



Thus, we have created circularly polarized light! The polarization rotation direction, right or left, will depend on which way the axes of the quarter-wave plate are oriented.

Note: Both optical activity and circular polarization can be left- or right-handed, but the two phenomena are completely different otherwise. A sugar solution rotates the direction of polarization, but you still get linearly polarized light out. A circular polarizer does not produce linearly polarized light. A 1/4-wave plate does not rotate the direction of polarization as optically active materials do (Section 4.5). It is the electric field vector that rotates at the frequency of light in circular polarization.

- Notice that the order in which light passes through the filters is important. You must first linearly polarize the light before applying the  $90^\circ$  phase shift. If you do it the other way around, you just get linearly polarized light. You can check this with your filters. What happens to circularly polarized light when it passes through a linear polarizer? Try to explain why.

Evidently, from what you have just seen, there is a distinct difference between circular polarization and linear polarization. Recall that Equation 4.3 described a wave linearly polarized along the  $x$ -axis. The equivalent forms for right and left circularly polarized waves are respectively:

$$\begin{aligned}\mathbf{E}_0(z, t) &= \frac{E_0}{\sqrt{2}} \cos(kz - \omega t) \hat{\mathbf{x}} + \frac{E_0}{\sqrt{2}} \sin(kz - \omega t) \hat{\mathbf{y}} \quad \text{and} \\ \mathbf{E}_0(z, t) &= \frac{E_0}{\sqrt{2}} \cos(kz - \omega t) \hat{\mathbf{x}} - \frac{E_0}{\sqrt{2}} \sin(kz - \omega t) \hat{\mathbf{y}}\end{aligned}\tag{4.8}$$

Although these equations look similar to Equation 4.4, the behavior is somewhat different. In Equation 4.8, the  $x$ - and  $y$ -components are  $90^\circ$  out of phase – when the  $x$ -component is maximum the  $y$ -component is zero and vice-versa. For linearly polarized light, the  $x$ - and  $y$ -components are exactly in phase and therefore rise and fall together.

The next question is: what happens when circularly polarized light is reflected by a metal surface? At the surface, the response of conduction electrons to any applied electric field guarantees that the sum of electric fields from the incident and reflected rays must always equal zero. If an incoming right-circular ray can be represented by:

$$\mathbf{E}_I(z, t) = \frac{E_0}{\sqrt{2}} \cos(kz - \omega t) \hat{\mathbf{x}} + \frac{E_0}{\sqrt{2}} \sin(kz - \omega t) \hat{\mathbf{y}}\tag{4.9}$$

the reflected ray must be

$$\mathbf{E}_R(z, t) = -\frac{E_0}{\sqrt{2}} \cos(-kz - \omega t) \hat{\mathbf{x}} - \frac{E_0}{\sqrt{2}} \sin(-kz - \omega t) \hat{\mathbf{y}}\tag{4.10}$$

so that at the metal surface,  $z=0$ , the sum of the two fields,  $\mathbf{E}_I$  and  $\mathbf{E}_R$  is identically zero.

We would like to characterize the polarization of the reflected beam described by Equation 4.10. To do this, we need a new set of coordinate axes that correspond to light traveling in the positive direction. The required transformation is

$$\begin{aligned}\hat{\mathbf{x}}' &= -\hat{\mathbf{x}} \\ \hat{\mathbf{y}}' &= +\hat{\mathbf{y}} \\ \hat{\mathbf{z}}' &= -\hat{\mathbf{z}}\end{aligned}\quad (4.11)$$

The sign change for  $\hat{\mathbf{z}} \rightarrow \hat{\mathbf{z}}'$  has the desired effect of describing a wave moving in the positive  $z'$  direction; the sign change,  $\hat{\mathbf{x}} \rightarrow -\hat{\mathbf{x}}'$ , maintains a right-handed coordinate system, *i.e.*,  $\mathbf{x} \times \mathbf{y} = \mathbf{z}$ . With these transformations, the reflected wave is:

$$\mathbf{E}_R(z, t) = \frac{E_0}{\sqrt{2}} \cos(kz' - \omega t) \hat{\mathbf{x}}' - \frac{E_0}{\sqrt{2}} \sin(kz' - \omega t) \hat{\mathbf{y}}' \quad (4.12)$$

Compared to the original wave, there is a sign change for the y-component of the electric field. This corresponds to a reversal from an incident right circular polarization to a reflected left circular polarization. This is the reason the back reflected light from a metal surface is completely absorbed by a circular polarizer (this trick is sometimes used to reduce glare from external light sources that reflect from the surface of computer display monitors).

There is a more graphic way of viewing what's going on here. The motion of circularly polarized light can be likened to the twisting of a screw. The process of reflection in a mirror turns a right-handed screw into a left-handed screw and vice versa.

## 4.7 Make Your Own Circular Polarizer

Your kit has two clear filters (and one  $2.5 \times 7.5$  cm microscope slide). One of the filters is a 1/4-wave plate and the other is a 1/2-wave plate (hopefully). As we have discussed, if we put a linear polarizer next to a 1/4-wave plate, we can get a circular polarizer if we do it the right way. From the techniques introduced in Section 4.6 you should be able to:

- Identify the 1/4-wave plate
- Make your own R polarizer
- Make your own L polarizer. (Note: Since you don't know which is the fast axis on the 1/4-wave plate, you can't know whether you make an R or L polarizer. Never mind. Arbitrarily call one R and one L. In Section 4.9 you will perform a simple experiment to find out which is which.)

- Test whether you did all these steps correctly. Mark the 1/4-wave plate. Does it make any difference which side of the 1/4-wave plate is next to the linear polarizer in your home-made circular polarizer? (Flip it!)
- Now that you know how to make your own circular polarizer you may want to check whether the circular polarizers in your kit are made similarly, namely, by bonding a linear polarizer to a 1/4-wave plate. In fact if you followed Section 4.3 conscientiously, you already have the answer. Is light that passed through a circular polarizer linearly polarized? How would you find out? Record your answer in your notebook.

## 4.8 Determining the Handedness of Light!

Determining which of your circular polarizers is left, and which is right, is easy, once you know some basic physics about how your 1/4-wave plate works.

The 1/4-wave plate and 1/2-wave plates in your optics kit are really nothing more than a bit of stretched plastic. All plastic is made of long chain molecules known as *polymers*. Plastic gets its plastic properties because these molecules are all tangled up together, like cooked spaghetti.

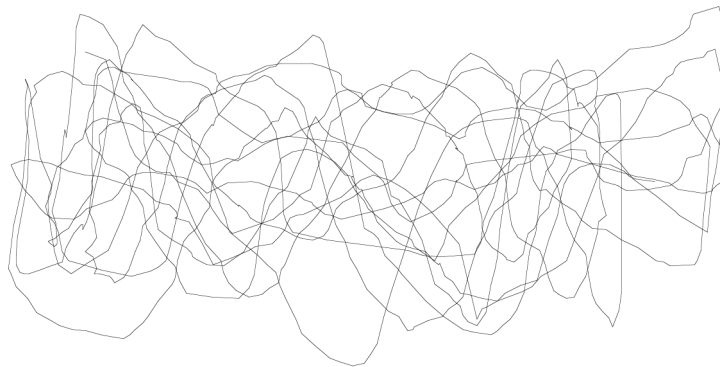


Figure 4.5 Cooked spaghetti, or unstretched polymer plastic

If you stretch a piece of plastic wrap or a plastic bag, it deforms – it actually changes its shape, long before it tears. This is the very property that we call *plastic* deformation, in fact. At the molecular level, the long polymer molecules don't change their length, but they do all start to pull into alignment. So stretched plastic has the polymers more-or-less lined up.

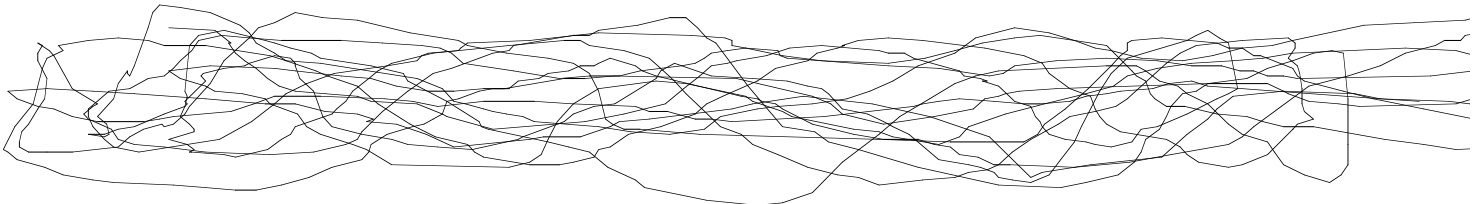


Figure 4.6 Stretched polymer plastic, or stretched cooked spaghetti.

Light that is polarized *parallel* to the lined up molecules sees a higher index of refraction than light polarized *perpendicular* to the molecules. Parallel-polarized light consequently moves *slower* through the plastic. **The stretched axis is therefore called the “slow” axis in the plastic. The axis perpendicular to the stretch direction is called the “fast” axis.** Physically, this is because the electrons in the polymer respond more to the electric fields in light when those fields are directed along the bonds between atoms molecule, than when the fields are perpendicular to it. In Lab 3 you learned that light travels at different speeds through different materials. Now here is something new: light with different polarizations travels at different speeds in the same material, if the material is *anisotropic*.

If light going through the plastic is polarized in between the fast and slow directions, then the fast and slow components of the polarization vector each do their own thing: The component of electric field along the slow axis travels more slowly than the perpendicular component traveling along the fast direction. The slow component falls behind the fast component. In a 1/4-wave plate, the slow component falls behind the fast component by a quarter of a cycle. That means that if the light entering oscillates like  $\cos(\omega t)$ , the slow component will come out oscillating like  $\sin(\omega t)$ . This is precisely the required property to turn linearly polarized light (Equation 4.6) into circularly polarized light (Equation 4.7).

- The figure below shows linearly polarized light entering a 1/4-wave plate. Copy this figure into your notebook, and label the following:
- Show the fast axis.
- Show the slow axis.
- Draw an arrow on the circle showing the direction of circulation of the electric field after it leaves the polarizer. The light is incident from the lower left

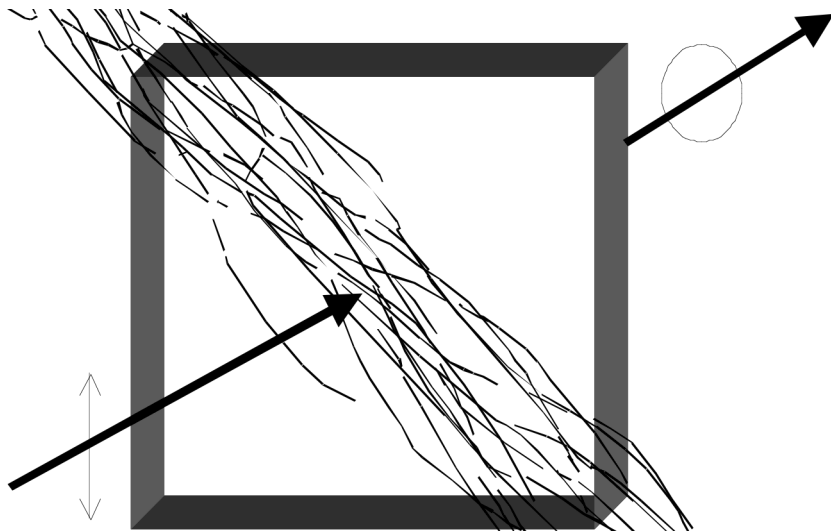


Figure 4.7 Linearly polarized light passes through plastic stretched at  $45^\circ$  with respect to the polarization of the light. On the other side, the light is circularly polarized.

There are two different systems for labeling the circular polarization of light. The first method uses the “right-hand rule.” Using your right hand, point the thumb in the direction of the light propagation. Your fingers will then curl in the direction of motion of the rotating electric field if the light is “right-handed” (RH). If the electric field rotates the other way, the light is called “left handed” (LH). This method of labeling right and left polarization is called the “**handedness convention.**”

- After the light in Figure 4.7 passes through the quarter-wave plate, is it right handed or left handed?

The other convention for labeling the light uses the similarity between the spiral corkscrew shape of the electric field vector along the axis of propagation of the light, and the spiral of the threads on a screw. This is called the “**screw convention.**” Light whose electric field spirals through space like an ordinary screw is called “right circularly polarized” (RCP) because the thread spiral on ordinary screws is conventionally called a “right-handed thread”. If the electric field spirals in space like a left handed thread, it’s called “left circular polarization” (LCP). Now, here’s a curious fact you can discover on your own:

- Using diagrams of the corkscrew shape of a circularly polarized electric field, drawn in your notebook, show that “right-handed” (RH) light according to the **handedness convention** is “left circularly polarized” (LCP) according to the **screw convention**. Also, show that “left-handed” (LH) light is “right circularly polarized” (RCP). So, two reasonable and intuitive conventions happen to use the opposite words (right and left) to describe the same state of circular polarization! *Don’t get confused!* Most physicists use the handedness convention, but optical physicists know both, and now so do you. The screw convention is based on a “snapshot” of a light wave; at any instant the electric field traces out either a left-handed or right-handed spiral. The handedness convention is based on how the direction of the electric field varies with time as the circularly polarized light passes a particular point in space.

## 4.9 Construct your own 1/4-wave plate

Cellophane tape (NOT Scotch Magic tape) is an excellent plastic material for constructing your own 1/4-wave plate.

- Stretch some clear cellophane tape using your fingers, and then stick it down to the microscope slide in your optics kit. This will take a little practice, but you should be able to stretch it just enough to make a region with good 1/4-wave retardation. Use a narrow strip so you can stretch it quite a bit. Clear polyethylene or food wrap also works, but you may have to stretch it until it almost breaks. Now, combine this with a linear polarizer to make a polarizer for right-handed light. Test your 1/4-wave plate using reflection as described in Sect. 4.7.

You are now ready to use your new polarizer to make a real measurement. But first, take a look at the following list of facts, and make sure that they make sense to you, based on what you have observed and learned:

### **Some Facts about Circular Polarizers**

1. To produce circularly polarized light, the light must go through the linear polarizer first, then the 1/4-wave plate. If you send it through the other way, you get linear polarized light.
2. To analyze circularly polarized light, the light must go through the 1/4-wave plate first, then the linear polarizer.
3. A right-handed analyzer will not pass left-hand polarized light and vice-versa.
4. If circularly polarized light is reflected, the handedness reverses.
5. 1/4-wave plates are true quarter wave retarders only for one wavelength (usually chosen to be green light) because it is near the center of the visible spectrum. For other wavelengths the plate will shift the two polarization components by more or less than  $90^\circ$ . Since a circular polarizer contains a 1/4-wave plate, it will work best at the design wavelength of the 1/4-wave plate while for other wavelengths the transmitted light will be elliptically polarized. Thus if you put an L and an R polarizer back-to-back, instead of complete extinction, you get some blue light transmitted. Linear polarizers do not involve 1/4-wave plates and give nearly complete linear polarization over the entire visible spectrum.

- Use your home-made polarizer to test the two circular polarizers in your optics kit. Now you can tell which is which! Label the appropriate polarizers “RH” or “LH.” (Note: you could also label them “RCP” and “LCP” if you want, but remember the screwy convention is opposite to the handedness convention!) **TAPE THE LABELED CIRCULAR POLARIZERS INTO YOUR LAB BOOK SO THAT WE CAN CHECK IF YOU DID THIS RIGHT.**

## 4.10 The 1/2-wave Plate

The 1/2-wave plate has a fast and a slow axis just like the 1/4-wave plate, but it does not produce circularly polarized light. Let us imagine a linear polarizer at  $45^\circ$  in front of the 1/2-wave plate. The component of  $\mathbf{E}$  along the slow axis is retarded by one-half cycle or  $180^\circ$ . If the light beam after the first polarizer is described by:

$$\mathbf{E}_0(z, t) = \frac{E_0}{\sqrt{2}} \cos(kz - \omega t) \hat{\mathbf{x}} + \frac{E_0}{\sqrt{2}} \cos(kz - \omega t) \hat{\mathbf{y}} \quad (4.13)$$

Then following the 1/2-wave plate, the field is

$$\mathbf{E}_0(z, t) = \frac{E_0}{\sqrt{2}} \cos(kz - \omega t) \hat{\mathbf{x}} - \frac{E_0}{\sqrt{2}} \cos(kz - \omega t) \hat{\mathbf{y}} \quad (4.14)$$

- Try such a combination of linear polarizer and 1/2-wave plate and analyze the direction of polarization of the light that went through it. What happens when you rotate one filter? Record your result (you need two linear polarizers, one in front and one behind the 1/2-wave plate). Explain.
- What happens to circularly polarized light when it passes through a 1/2-wave plate? Verify your prediction with a simple test using the components in your optics kit. Explain.

## 4.11 Reflection Again

- Now try to predict what will happen when you slip a 1/4-wave plate between the circular polarizer and the metal surface. Record your prediction; then try. Explain the result.
- Can you predict what will happen when you slip the 1/2-wave plate between the circular polarizer and the metal (or both the 1/4- and 1/2-)? Again record your prediction; then try it.
- Can you predict what will happen when you pass linearly polarized light through your sugar solution, then reflect it in a mirror and send it back through the sugar solution? Record your prediction and try it.

- Get a piece of aluminum foil and put one of your circular polarizers on top of it so that the foil looks dark (blue). You are already familiar with this effect. Now lift the polarizer slightly off the foil, so that you can see the shadow of the polarizer on the metal. Why is only the shadow dark?
- Make a V-shaped crease in the aluminum foil. Use illuminations such that most of the light comes from a definite direction (a lamp or a window). Put the circular polarizer back on the creased foil. Does the crease look light or dark? Explain? (Hint: When you look at your right hand in a single mirror, it looks like a left hand. What does it look like in a double mirror made by joining two mirrors at right angles?)
- If you look through a linear polarizer at light reflected off your plastic box you will see colors. Even without the polarizer you can see faint colors if the light is right. Explain.



## Appendix 4.A – Optical Rotation

Assume a beam of light linearly polarized along the  $\hat{x}$  axis:

$$\mathbf{E}_{LP} = E_0 \cos(kz - \omega t) \hat{x} \quad (4.15)$$

where  $k = 2\pi / \lambda$  and  $\omega = 2\pi f$ . Circularly polarized light can be represented by the expressions:

$$\mathbf{E}_{RCP} = E_0 (\cos(kz - \omega t) \hat{x} + \sin(kz - \omega t) \hat{y}) \quad (4.16a)$$

$$\mathbf{E}_{LCP} = E_0 (\cos(kz - \omega t) \hat{x} - \sin(kz - \omega t) \hat{y}) \quad (4.16b)$$

Thus the linearly polarized beam given in Equation 4.15 can be rewritten as:

$$\mathbf{E}_{LP} = \frac{1}{2} \mathbf{E}_{RCP} + \frac{1}{2} \mathbf{E}_{LCP} \quad (4.17)$$

Now imagine this beam enters a medium which has slightly different propagation velocities for light with opposite circular polarity. After some distance, the phase of one wave will be slightly advanced with respect to the other:

$$\begin{aligned} \mathbf{E}_{LP} = & \frac{E_0}{2} [\cos(kz - \omega t + \delta) \hat{x} + \sin(kz - \omega t + \delta) \hat{y}] \\ & + \frac{E_0}{2} [\cos(kz - \omega t) \hat{x} - \sin(kz - \omega t) \hat{y}] \end{aligned} \quad (4.18)$$

Since

$$\begin{aligned} \cos \alpha + \cos \beta &= 2 \cos\left(\frac{\alpha + \beta}{2}\right) \cos\left(\frac{\alpha - \beta}{2}\right) \\ \sin \alpha - \sin \beta &= 2 \cos\left(\frac{\alpha + \beta}{2}\right) \sin\left(\frac{\alpha - \beta}{2}\right) \end{aligned} \quad (4.19)$$

we can rewrite Equation 4.18 as:

$$\mathbf{E}_{LP} = E_0 \cos\left(kz - \omega t + \frac{\delta}{2}\right) \left[ \cos\left(\frac{\delta}{2}\right) \hat{x} + \sin\left(\frac{\delta}{2}\right) \hat{y} \right] \quad (4.20)$$

This is a plane polarized wave with the polarization twisted by an angle  $\delta/2$  from the  $x$ -axis towards the  $y$ -axis. This effect, called optical rotation, occurs whenever light passes through a substance containing molecules with a preferential screw direction. Such constituents are omnipresent in biological systems and their byproducts.

**Experiment 4 - Polarization****Apparatus List**

1. Polarization kit
2. 5/16" circular paper labels
3. Two 2" diameter polarizers
4. One 2" lens holder assembly
5. One rotary filter assembly
6. Green interference filter
7. Optical bench with lamp and light baffle
8. Glass tumblers for milk scattering
9. Laser support stand for optical rotation samples
10. Optical rotation samples, water, fructose, corn syrup, turpentine
11. Hewlett-Packard DVM
12. Hewlett-Packard model E3632A low voltage DC power supply
13. Photodiode box
14. Cardboard light shield
15. Coffee creamer
16. BNC to banana plug adapter