CHAPTER 1

LIGHT AS A WAVE

Before we get into quantum physics, let's understand the classical view of light. As early as 100 C.E., Ptolemy—a Roman citizen of Egypt—studied the properties of light, including reflection, refraction, and color. His work is considered the foundation of the field of optics. Ptolemy was intrigued by the way that light bends as it passes from air into water. Just drop a pencil into a glass of water and see for yourself!

As shown in Figure 1a, the pencil half under the water looks bent: light from the submerged part of the stick changes direction as it reaches the surface, creating the illusion of the bent stick. This effect is known as *refraction*, and the angle at which the light bends depends on a property of a material known as its *refractive index*.

In the 1600s, Dutch mathematician Willebrord Snellius figured out that the degree of refraction depends on the ratio of the two materials' different refractive indices. Most materials have a refractive index greater than 1, which means that as light enters the material from air, the angle of the ray in the material will become closer to perpendicular to the surface than it was before it entered. This is known as Snell's Law, which states that the ratio of the sines of the angles of incidence and refraction (θ_1, θ_2) is equal to the inverse ratio of the indices of refraction (n_1, n_2):

$$\frac{\sin \theta_1}{\sin \theta_2} = \frac{n_2}{n_1}$$

Try it out yourself with a small laser pointer! As shown in Figure 1b, partially fill a small aquarium with water. Disperse some milk in the water to make it a bit cloudy, which will make the laser beam visible. Use smoke from a smoldering match or candle to make the laser beam visible in the air above.

Measure the angles between the rays and a line perpendicular to the water surface. The refraction coefficient for water is approximately $n_2 = 1.333$, and for air is more or less $n_2 = 1$. Do your measurements match Snell's Law?

NEWTON'S VIEW: LIGHT CONSISTS OF PARTICLES

In 1704, Sir Isaac Newton proposed that light consists of little particles of mass. In his view, this could explain reflection, because an elastic, frictionless ball bounces off a

Exploring Quantum Physics Through Hands-On Projects. By David Prutchi and Shanni R. Prutchi

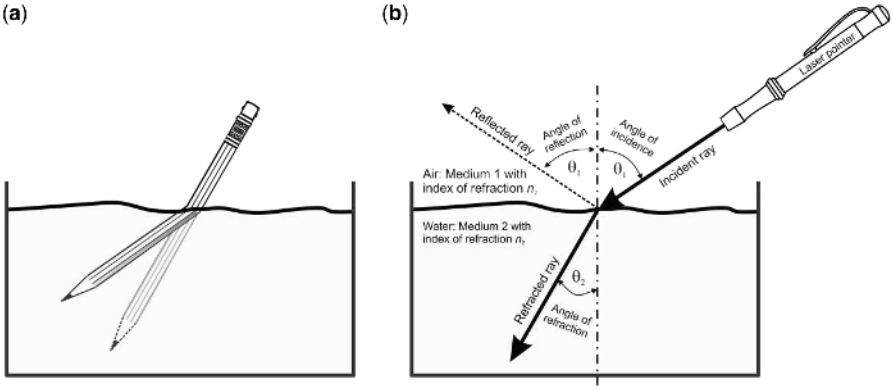

Figure 1 Refraction of light: **(a)** A pencil dipped in water appears distorted because refraction causes light to bend when it passes from one substance into another, in this case from air to water. **(b)** A laser pointer clearly demonstrates Snell's law of diffraction.

smooth surface just like light bounces off a mirror—that is, the angle of incidence equals the angle of reflection.

Remember that Newton was very interested in the way masses attract each other through the force of gravity. In his view, this force was responsible for refraction at the boundary between air and water. Newton imagined that matter is made up of particles of some kind, and that air would have a lower density of these particles than water. This is not far from what we know today—we would call Newton's particles "molecules" and "atoms." Newton then proposed that there would be an attractive force, similar to gravity, between the light particles and the matter particles.

Now, when a light particle travels within a medium, such as air or water, it is surrounded on all sides by the same number of matter particles. Newton explained that the attractive forces acting on a light particle would cancel each other out, allowing the light to travel in a straight line. However, near the air–water boundary, the light particle would feel more attracted by water than by air, given the water's higher density of "matter particles." Newton proposed that as the light particle moves into the water, it experiences an attractive force toward the water, which increases the light particle's velocity component in the direction of the water, but not in the direction parallel to the water.

This velocity increase in the direction perpendicular to the air–water boundary would deflect the light closer to perpendicular to the surface, which is exactly what is observed in experiments. Newton thus claimed that the velocity of light particles is different in different transparent materials, believing that light would travel faster in water than in air. (We now know this is not the case, but we'll get to that in a minute.)

Newton didn't equate gravity with the attractive force between matter particles and light particles. He needed this force to be equal for all light particles crossing the boundary between two materials to explain how a prism separates white light into the colors of the rainbow. Newton proposed that the mass of a light particle depended on its color. In his view, red light particles would be more massive than violet light particles. Because of their increased inertia, red light particles would thus be deflected less when crossing the boundary between materials.

Newton's greatness conferred credibility to his theory, but it was not the only one around. Dutch physicist Christiaan Huygens had proposed an earlier, competing theory: light consists of waves. This was supported by the observation that two intersecting beams of light did not bounce off each other as would be expected if they were composed of particles. However, Huygens could not explain color, and the wave versus particle debate for the nature of light raged until decisive experiments were carried out in the nineteenth century.

YOUNG'S INTERFERENCE OF LIGHT

Around 1801, Thomas Young discovered interference of light. This phenomenon is only possible with waves, providing conclusive evidence that light is a wave. In Young's experiments, light sent through two separate slits results in a pattern that is very similar to the one produced by the interference of water waves shown in Figure 2.

Let's spend some time experimenting with water waves before we go on to reproducing Young's experiments on the interference of light. Start by building a ripple tank, as shown in Figure 3, out of a glass baking pan (for example, a Pyrex® rectangular pan), some wood, two rubber bands, and a vibrating motor made for pagers and cellular phones.

The waves in the shallow layer of water are better observed by illuminating them from above to cast shadows through the glass bottom onto a white sheet of paper 50 cm below the tank. Use a spotlight, not a floodlight for illumination. Even better, use a strobe light (like the ones used by party DJs) to "freeze" the waves in place. Fill the pan with water to a depth of around 5 mm, and then fit pieces of metal sponge around the edges of the tank to reduce unwanted wave reflections from the pan's

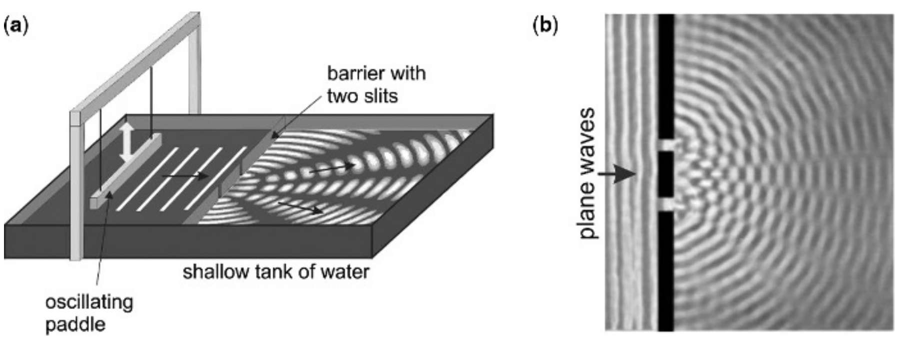

Figure 2 Water waves from two sources interfere with each other to form a characteristic pattern: **(a)** A ripple tank is a shallow glass tank of water used to demonstrate the basic properties of waves. In it, a shaking paddle produces waves that travel toward a barrier with two slits. **(b)** Plane waves strike two narrow gaps, each of which produces circular waves beyond the barrier, and the result is an interference pattern.

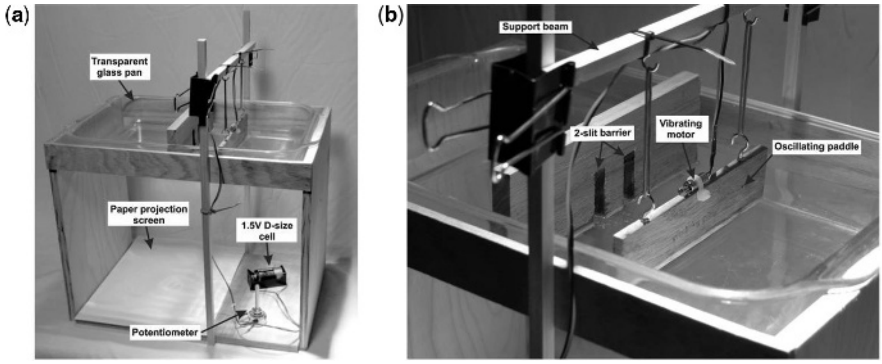

Figure 3 In our home-built ripple tank, a wooden stand supports a glass baking pan a distance away from a white sheet of paper. **(a)** With a light shining from above, ripples on a shallow layer of water in the pan are projected as shadows on the paper. **(b)** A small vibrating motor attached to a suspended beam just touching the water surface produces plane waves with which we can conduct experiments on wave reflection, refraction, and interference. For the sake of clarity, these pictures don't show the steel wool padding that we use to absorb reflections at the tank walls.

walls. Test the setup by dimming the room lights and lightly dipping a pencil into the water to create ripples.

To generate continuous plane waves, attach the vibrating motor to a wooden beam. Use rubber bands to suspend the beam from a support beam, and adjust the height of the vibrating beam so that it just touches the water surface. Power the motor from a 1.5-V D cell through a 100 Ω potentiometer (e.g., Clarostat 43C1-100).

Next, set up two straight barriers with a short one between them, along a line parallel to the vibrating beam. Make the gaps between barriers about 1-cm wide. Turn the potentiometer to generate straight waves with a wavelength of about 1 cm. Try different separations between the slits, and see if your data agree with the equation:

$$d = \frac{\lambda r}{s}$$

where d is the fringe separation (e.g., between the central fringe and the first fringe to its side), λ is wavelength, s is the distance between the slits, and r is the distance from the 2-slit barrier to the point where the fringes are observed.

Thomas Young did essentially the same thing using colored light instead of water waves. We will use inexpensive laser pointers and a simple double slit to replicate the experiment that Young performed to support the theory of the wave nature of light (Figure 4). Instead of making a double-slit slide,* we use one made by Industrial

*A double-slit slide can be made at home by coating a piece of clear glass with dark paint and then scoring the double slit with two narrowly-spaced razor blades. The best way to produce a quality slide is to apply two parallel strips of adhesive tape, leaving a $\frac{1}{2}$-in. band of glass uncovered. A large drop of paint applied toward one end of the bare strip is then spread with a razor blade along the strip to deposit a very smooth, constant-thickness layer of paint. Two brand-new razor blades should then be stacked, using a paper spacer between them. The two parallel blades should then be used with a brisk motion to score a pair of lines across the dry paint. The result should be two hairline transparent slits separated by an extremely thin line of paint.

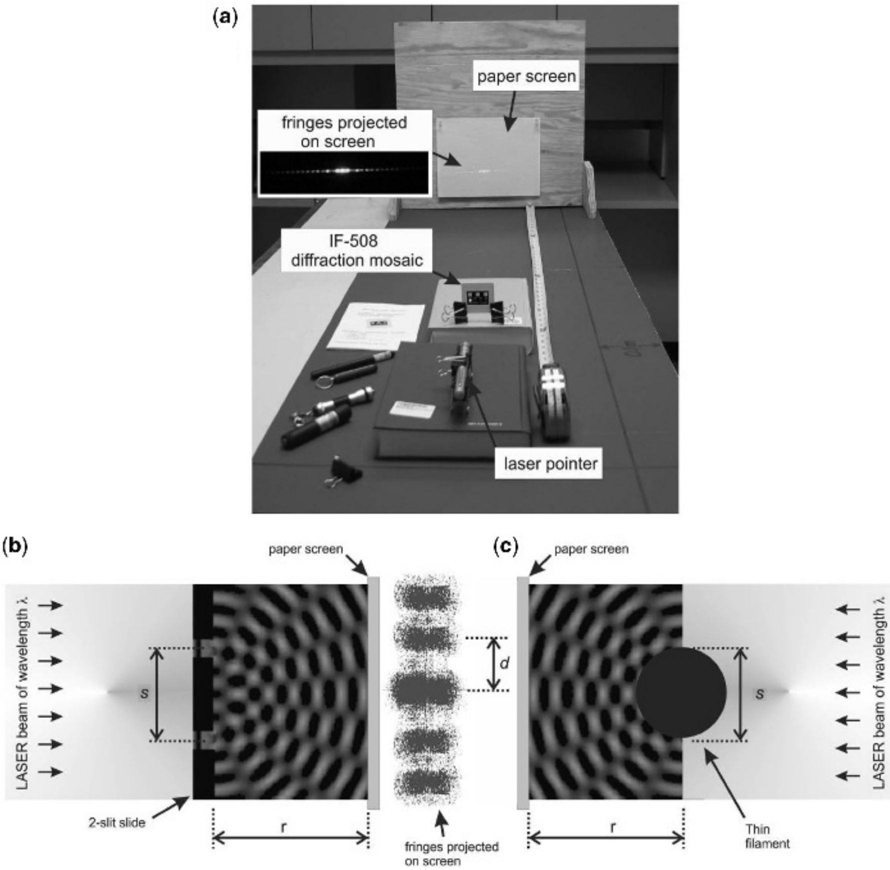

Figure 4 A modern version of Young's experiment to demonstrate the wave nature of light. **(a)** All that is needed is an inexpensive laser pointer and a slide with two slits. **(b)** The separation between fringes is related to the distance between the slits according to $d = \lambda r/s$. **(c)** A thin filament of thickness s produces the same interference pattern as a double slit of the same separation.

Fiber-optics. Their model IF-508 diffraction mosaic is a low-cost ($6) precision array of double slits and gratings for performing laser double- and multiple-slit diffraction experiments. The mosaic is mounted in a 35-mm slide holder and contains four double slits and three multiple-slit arrays on an opaque background with clear apertures. Double-slit separations range from 45 to 100 μm in width. The gratings are 25, 50, and 100 lines/mm.

Interestingly, Young found that the separation between fringes is related to the distance between the slits exactly through the same equation as the water analog:

$$d = \frac{\lambda r}{s}$$

TABLE 1 Calculated and Measured Double-Slit Interference Distance Between Center and First Bright Fringe for s = 45 μm at Different Wavelengths

Laser pointer	Wavelength λ [nm]	Measured fringe separation d [mm]	Calculated fringe separation d [mm]
Red	630	13.8	14
Green	532	11.8	11.8
Violet	405	8.6	9

where s is the distance between slits, λ is the wavelength of the light, d is the separation between fringes (the distance between central maximum and each of the first bright fringes to its side), and r is the distance from the slits to the screen.

For the double slit marked "25 × 25" in the IF-508 diffraction mosaic, $s =$ 45 μm. Using red, green, and violet laser pointers with $r = 1$ m, we measured the fringe separations shown in Table 1.

The deviation between measured fringe separation and calculated fringe separation is because of our assessment of the location of the center of each fringe. Better accuracy can be obtained by repeated measurement and averaging. Try out this and other slit separations available in the IF-508 slide ($s = 5.8$, 7.5, and 10 μm) for yourself, and see how well the wave model accounts for the behavior of light.

Notice that $d = \lambda r/s$ is *not* dependent on the width of the slits, only on their separation. Interestingly, this same equation works when there are no slits at all. If one shines a laser pointer at a human hair in a dark room, the separation d between the interference fringes can be calculated by making s equal to the diameter of the hair.[1] Try it out! Shine a laser pointer at a hair and measure the distance between the interference fringes. Try to calculate the width of the hair—you should come up with a thickness of around 50 to 150 μm. Try to remember this, because the equivalence between a double-slit interference pattern and that obtained using a very thin filament will become very important in experiments that we will conduct later to expose quantum effects.

AUTOMATIC SCANNING OF INTERFERENCE PATTERNS

Accurately measuring interference patterns from projections on a screen is rather tedious. However, you can build a simple device that makes it possible to display interference patterns on an oscilloscope, making it easy to measure not only the distance between fringes, but also their amplitude.

As shown in Figure 5, the idea is to use a rotating mirror and a fast-light sensor to convert the interference pattern into an equivalent time-domain signal that can be displayed by a conventional oscilloscope. For the light sensor, we used a TAOS

TSL254R-LF light-to-voltage converter. This device is an inexpensive component that incorporates a light-sensitive diode and amplifier on a single chip. It is very easy to use. It requires a supply voltage in the range of 2.7 to 5.5 V (we use two 1.5-V AA batteries in series), and produces an output voltage that is directly proportional to the light intensity. We placed the light sensor behind a narrow slit built from two single-edge razor blades.

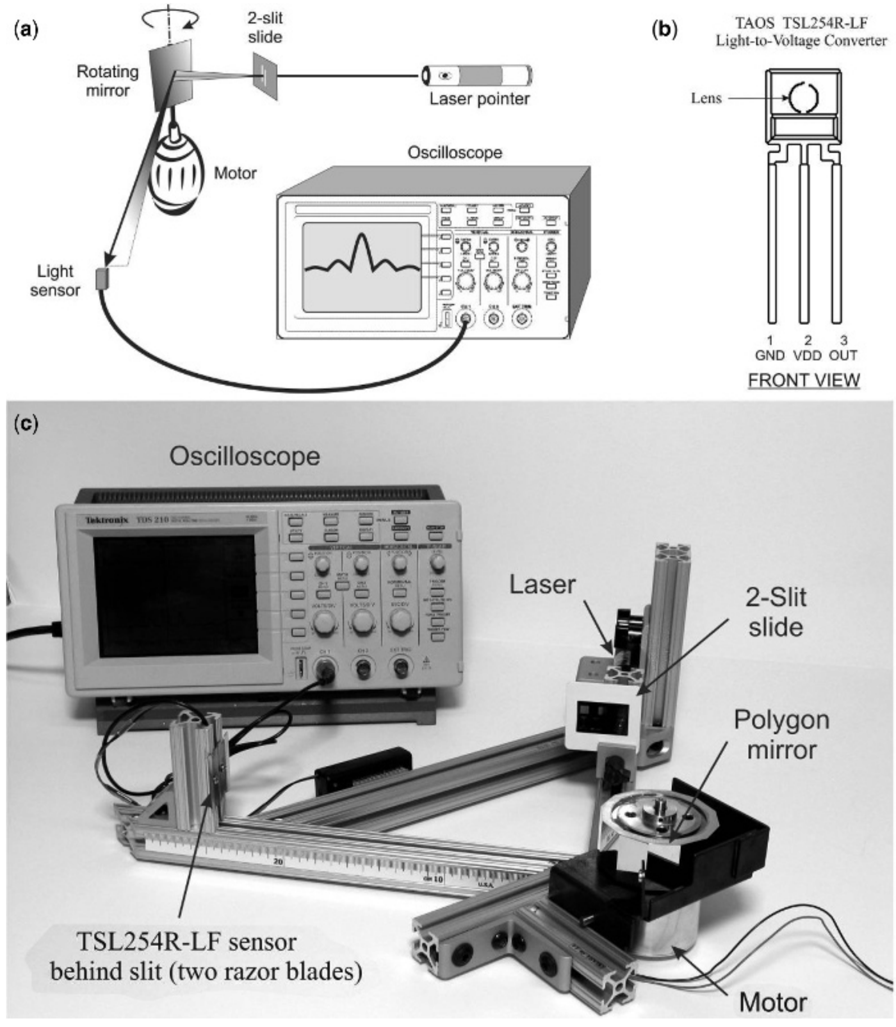

Figure 5 A simple scanner makes it easy to measure interference and diffraction patterns with an oscilloscope. **(a)** Simplified diagram of the basic concept. A small DC motor spins a mirror to scan the pattern onto a narrow-view light sensor, transforming the pattern's distribution along space into a signal that varies with time. An oscilloscope synchronized to the motor displays the pattern. **(b)** For the light sensor we used a TAOS TSL254R-LF light-to-voltage converter placed behind a narrow slit made from two razor blades. **(c)** We used a motor and polygon mirror from a broken bar-code scanner to build our setup.

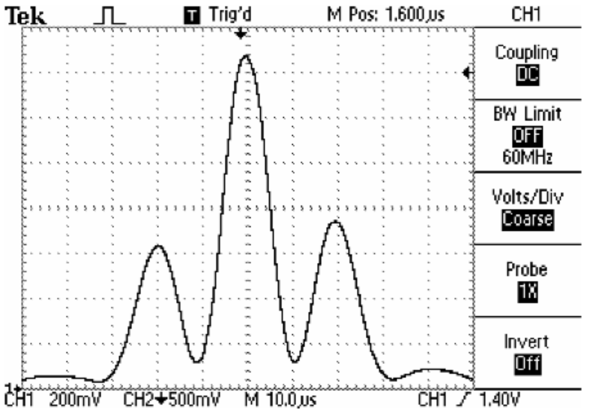

Figure 6 Interference pattern obtained with our scanner (Figure 5) for a double slit of $s = 10$-μm illuminated by a red (630-nm) laser pointer.

As shown in Figure 5c, we built the optical stand from 1-in. × 1-in. cross-section, T-slotted aluminum extrusions made by 80/20, Inc. These are meant for building office cubicles and machine frames, so they are widely available (e.g., from McMaster-Carr) and inexpensive. In spite of this, they are very rugged and sufficiently straight to perform optical experiments. Our motor and mirror came from a discarded supermarket bar-code scanner. However, you could rig a small front-surface mirror to the shaft of a small 2,000 to 4,000 rpm DC motor. The TSL254R-LF's response time (2 μs rise/fall time) is appropriate for these speeds. The advantage of a bar-code scanner motor is that it usually comes installed with a polygonal mirror and speed controller. Having more mirror surfaces per revolution reduces flicker if you are using an analog oscilloscope. The integrated controller maintains a constant rotation speed, which allows you to calibrate the system to produce a constant space-to-time relationship. Figure 6 shows a typical oscilloscope trace obtained with our system for a 10-μm slit spacing with a 630-nm red laser.

THE FINAL NAIL IN THE COFFIN FOR NEWTON'S THEORY OF LIGHT

Diffraction, reflection, and color are also explained by Young's wave theory. However, interference is the calling card of waves, so Young's experiments convinced many in the early 1800s that light is indeed a wave. In spite of this, Newton's reputation was so strong, that his particle model of light retained adherents until 1850, when French physicist Jean Foucault provided final, decisive proof that Newton's particle theory of light must be wrong. Remember that Newton's theory required the speed of light to be higher in water than in air? Well, Foucault experimentally showed the exact opposite. As shown in Figure 7, Foucault used a steam turbine to spin a mirror at the rate of 800 rps. He bounced a light beam off the rotating mirror; the beam was then reflected by a stationary mirror 9 m away. By the time the light returned to the rotating mirror, the mirror had rotated a little, causing the light to be deflected a certain amount away from the source.

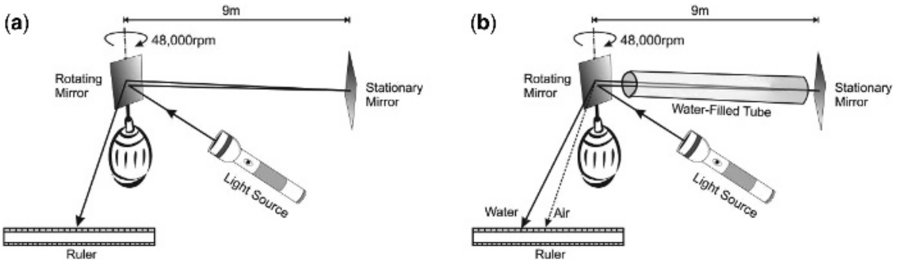

Figure 7 In 1850, Jean Foucault used this setup to measure the speed of light in **(a)** air and **(b)** water. He found that light travels more slowly in water than in air, contrary to the prediction of Newton's particle theory of light.

Foucault then placed a water-filled tube with transparent windows along the light path between the mirrors. If, as Newton affirmed, light travels faster in water than in air, the deflection angle would be smaller and the beam would arrive closer to the source.[†] Instead, Foucault found that introducing water in the optical path further delayed the beam, indicating that light travels more slowly in water than in air, contrary to the prediction of Newton's particle theory of light.

LIGHT AS AN ELECTROMAGNETIC WAVE

Later, in the 1860s, Scottish physicist James Clerk Maxwell identified light as an electromagnetic wave. Maxwell had derived a wave form of the electric and magnetic equations, revealing a wave-like nature of electric and magnetic fields that vary with time.

Maxwell figured out that an electric field that varies along space generates a magnetic field that varies in time and vice versa. For that reason, as an oscillating electric field generates an oscillating magnetic field, the magnetic field in turn generates an oscillating electric field, and so on. Together, these oscillating fields form the electromagnetic wave shown in Figure 8. The way in which an electromagnetic wave travels through space is described by its wavelength λ, while its oscillation in time is described by the wave's frequency. The frequency f and the wavelength are related through $c = \lambda f$, where c *is* the speed of light.

Because the speed of Maxwell's electromagnetic waves predicted by the wave equation coincided with the measured speed of light, Maxwell concluded that light itself must be an electromagnetic wave. This fact was later confirmed experimentally by Heinrich Hertz in 1887. Today, we use the electromagnetic spectrum at all wavelengths—from the enormously long waves that we use to transmit AC power, through the radio wavelengths that are the foundation of our wireless society, to the extremely short wavelengths of gamma radiation (Figure 9).

[†]A modern replication of Foucault's experiment is described in reference 2.

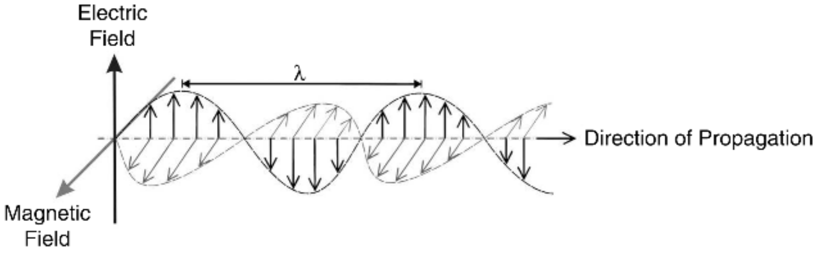

Figure 8 An oscillating electric field generates an oscillating magnetic field; the magnetic field in turn generates an oscillating electric field, and so on. Together these oscillating fields form an electromagnetic wave with wavelength λ that propagates at the speed of light *c*.

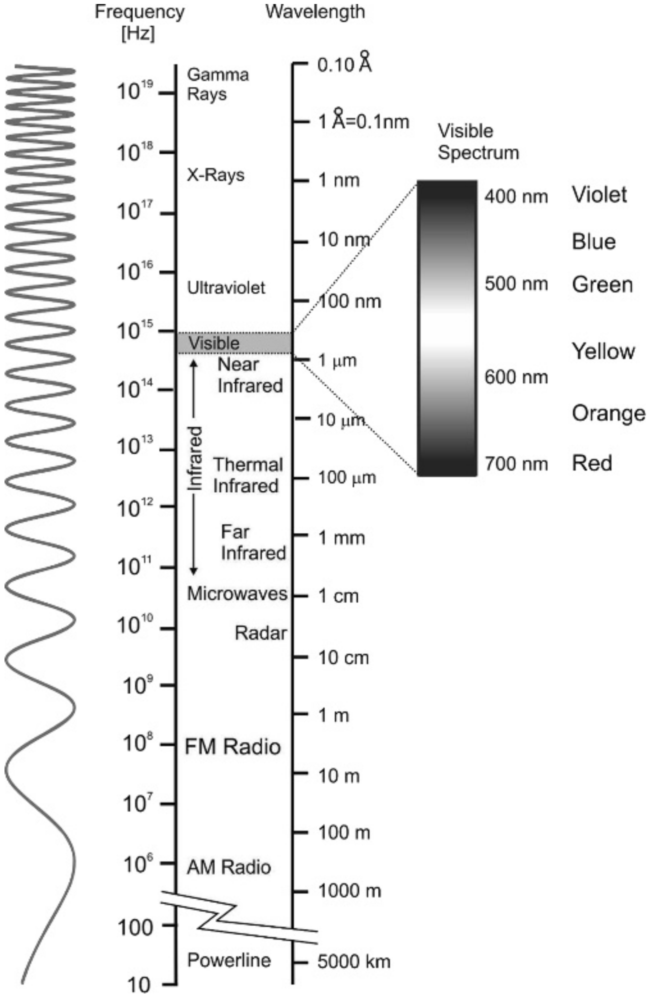

Figure 9 The electromagnetic spectrum. Maxwell concluded that light itself must be an electromagnetic wave. This fact was later confirmed experimentally by Hertz in 1887.

We understand that the only difference between visible light and the rest of the spectrum is that it is the range of electromagnetic waves to which our eyes are sensitive.

POLARIZATION

Polarization is an important characteristic of light that Maxwell's electromagnetic theory was finally able to explain. Notice in Figure 8 that the electric field is shown to oscillate in one plane, while the magnetic field oscillates on a perpendicular plane. The wave travels along the line formed by the intersection of those planes. The electromagnetic wave shown in this figure is said to be "vertically polarized," because the electric field oscillates vertically in the frame of reference we have chosen.

Light from most natural sources contains waves with electric fields oriented at random angles around its direction of travel. A wave of a specific polarization can be obtained from randomly polarized light by using a *polarizer*.

A polarizer can be made of an array of very fine wires arranged parallel to one another. The metal wires offer high conductivity for electric fields parallel to the wires, essentially "shortening them out" and producing heat. Because of the nonconducting spaces between the wires, no current can flow perpendicularly to them. As such, electric fields perpendicular to the wires can pass unimpeded. In other words, the wire grid, when placed in a randomly-polarized beam, drains the energy out of one component of the electric field and lets its perpendicular component pass with no attenuation at all. Thus, the light emerging from the polarizer has an electric field that vibrates in a direction perpendicular to the wires.

Although the wire-grid polarizer is easy to understand, it is useful only up to certain frequencies, because the wires have to be a fraction of the wavelength apart. This is difficult and expensive to do for short wavelengths, such as those of visible light. In 1938, E. H. Land invented the H-Polaroid sheet, which acts as a chemical version of the wire grid. Instead of long thin wires, it uses long thin polyvinyl alcohol molecules that contain many iodine atoms. These long, straight molecules are aligned almost perfectly parallel to one another. Because of the conductivity provided by the iodine atoms, the electric vibration component parallel to the molecules is absorbed. The component perpendicular to the molecules passes on through with little absorption.

As you will see throughout this book, understanding polarization is very important when experimenting with quantum physics, so we would like for you to gain an intuitive feel for this interesting property of waves.

OPTICS WITH 3-cm WAVELENGTH "LIGHT"

Let's start by experimenting with a polarizer that is actually made out of wires, such as the one shown in Figure 10. However, we'll need a source of electromagnetic waves with sufficiently large wavelength. Fortunately, it is easy to generate and detect

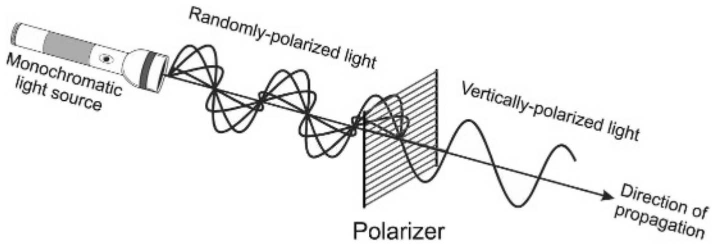

Figure 10 A parallel-wire polarizer absorbs electric field lines that are parallel to the wires. Only the perpendicular electrical field component of light is allowed to pass, producing light that is polarized perpendicularly to the direction of the wires.

microwaves with a wavelength of around 3 cm, making it possible to experiment with "optical" components scaled up to very convenient dimensions. Using a 3-cm microwave wavelength transforms the scale of the experiment. Measurements that would require specialized equipment at optical wavelengths to deal with submicrometer dimensions are easily accomplished with a simple ruler at 3-cm wavelengths.

As shown in Figure 11, a simple microwave transmitter can be built using a Gunnplexer,[3,4] which is a self-contained microwave module based on a specialized diode invented by John B. Gunn in the early 1960s. When a DC voltage is applied to the Gunn diode, current flows through it in bursts at regular intervals in the 10- to 100-GHz (10^{10} to 10^{11} Hz) range. These oscillations cause a wave to be radiated from the Gunnplexer's output slot.

You can find a Gunnplexer to use by taking apart a surplus microwave door opener or speed radar gun. The typical power output of Gunnplexers for these

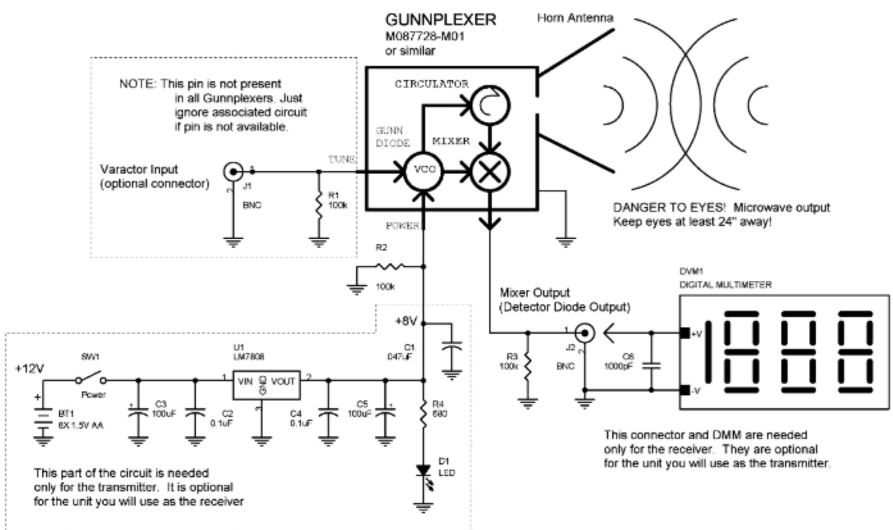

Figure 11 Schematic diagram for the Gunnplexer microwave transmitter/receiver. Two identical units can be built, but one simplified transmitter and one simplified receiver can also be used in these experiments.

applications is in the 5- to 10-mW range, and they commonly operate in either the so-called X-band (at 10.5 GHz) or K-band (24.15 GHz). For the receiver, you will need a second Gunnplexer built to operate in the same frequency range as your transmitter Gunnplexer, but this time you will use the microwave detector diode that is part of these modules.

As shown in Figure 12, we used surplus MO87728-M01 Gunnplexers, but almost any other model should work just as well. Aluminum die-cast boxes made by Bud Industries (model AN-1317) made nice enclosures for the transceivers. We bought the metallized-plastic horn antennas from Advanced Receiver Research.

A word of caution regarding the use of Gunnplexers: although the microwaves generated by Gunnplexers will not cook you, the output is sufficiently concentrated that it could cause eye damage at very close range. It is wise to never look at close range into the open end of a Gunnplexer while it operates.

Now to our experiments. Place the Gunnplexers about a meter apart and point the antennas at each other. Connect a digital voltmeter to the detector diode of your receiving Gunnplexer (the "mixer" output). Turn on the transmitter. The highest voltage across the mixer diode should appear when the Gunnplexers are oriented in the same plane. This is because Gunnplexers are polarized transmitters and receivers of microwaves. The electric field of the transmitted wave oscillates in the same orientation as the Gunn diode, and the detector is sensitive to fields in the same orientation

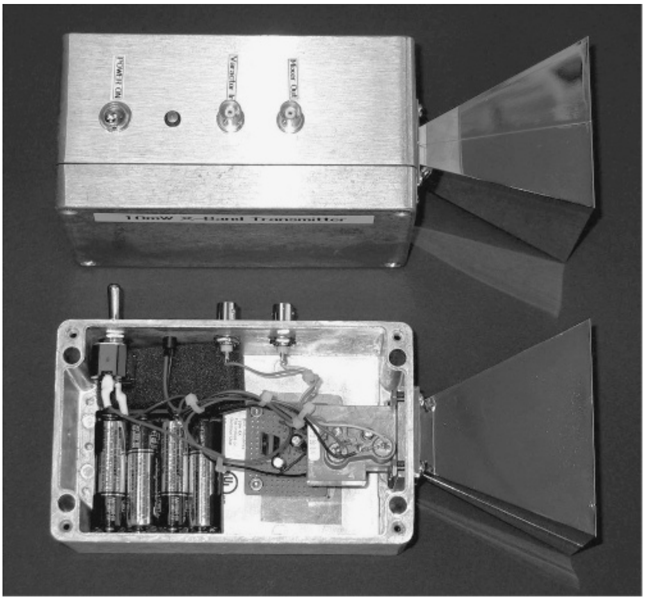

Figure 12 These are the X-band 10.5-GHz transmitter/receivers that we built from surplus Gunnplexer modules. Polarized microwaves with a wavelength of approximately 3 cm are launched from the horn antenna when the Gunn diode is powered. The "Mixer" diode in a second Gunnplexer is used to detect microwaves. It produces an output voltage proportional to the intensity of a properly polarized microwave signal.

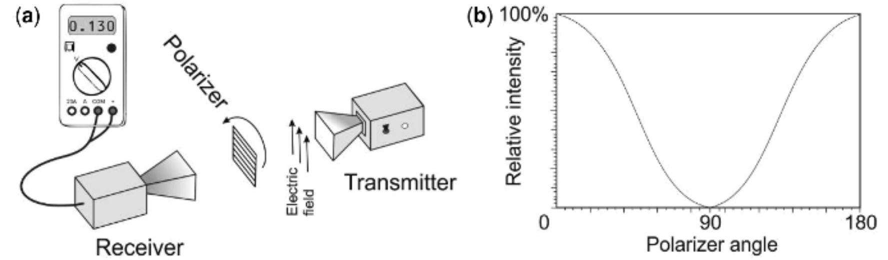

Figure 13 Experimenting with a polarizer. **(a)** Rotate a polarizer between two Gunnplexers that face each other. **(b)** Charting the voltmeter's measurements versus the polarizer angle should result in a graph similar to this one.

as the mixer diode. In our setup, we measure around 0.8 V output from the receiver when the horn antennas are placed right against each other. The signal drops down to 40 mV at a distance of 65 cm. You may note that the output voltage from the detector is negative with respect to ground. This is normal, and happens because of the way in which the mixer diode is internally connected within the Gunnplexer.

Next, you can build a polarizer by arranging copper wires in an array, just as in the idealized diagram of Figure 10. However, it is easier to use a circuit board made for prototyping—known as a stripboard—that already has conductors in an arrangement like the one we need. These boards are manufactured on an epoxy substrate that, fortunately for us, is virtually transparent to microwaves. Parallel copper tracks run along the board for hardwiring electronic components. These will act as the parallel wires for our polarizer. The whole board is usually perforated with a hole matrix, but the aperture of the holes is so small compared to the wavelength of the microwaves that they have no effect. For our microwave polarizers, we use stripboards manufactured by Vero. The specific one we use is the Veroboard™ 01-0021, which is sold for around \$10 each by many electronics supply stores, but any other stripboard should work just as well.

Take a 10-cm × 12-cm piece of stripboard and place it between the transmitting and the receiving Gunnplexers, as shown in Figure 13a. Knowing that the electric field

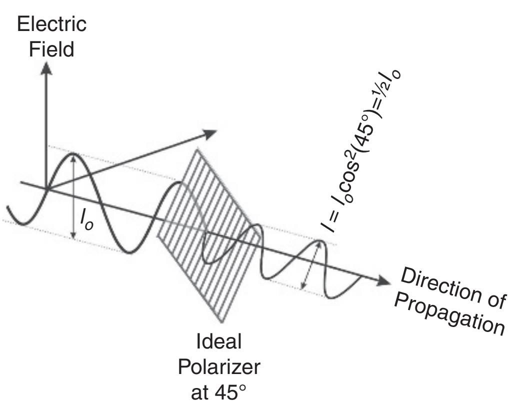

Figure 14 A polarizer actually shifts the polarization of an electromagnetic wave. The intensity of the exiting wave I is given by $I = I_o \cos^2 \theta_i$, where I_o is the initial intensity, and θ_i is the angle between the wave's initial polarization direction and the axis of the polarizer.

of the transmitted wave oscillates in the same orientation as the Gunn diode, can you predict how you should orient the polarizer to obtain the highest reading from the receiver? Using a protractor, graph the received intensity as you rotate the polarizer. You should end up with a graph that looks like the one in Figure 13b.

Next, take the polarizer out of the way and rotate the transmitter 90°. The signal at the receiver should drop close to zero. This makes sense, right? After all, the sensitive orientation of the receiver's detector diode is orthogonal to the electric field of the waves produced by the transmitter. Insert the polarizer at 0° and 90° referenced to the transmitter's polarization. The receiver still shows no signal. No surprise there . . . Now, rotate the polarizer to 45°. You should suddenly detect a signal. How can inserting the polarizer increase the signal level at the detector?

Look at Figure 14. Placing a polarizer at 45° introduces a component of the wave parallel to the receiver's sensitive axis, so that some of the transmitted signal is detected. An ideal polarizer in this case would allow half of the signal intensity to go through, but the signal exiting the polarizer would be rotated to 45°. At this new

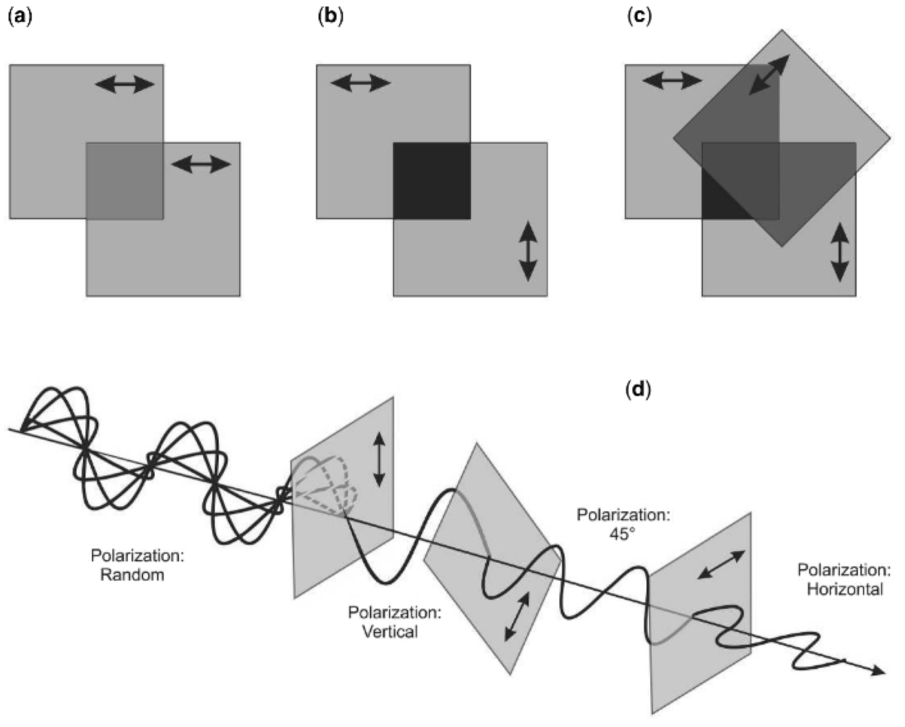

Figure 15 The intensity of light is cut by at least one-half when randomly polarized light is viewed through an ideal polarizer. **(a)** In practice, adding a second polarizer with the same orientation further attenuates the light, because real polarizers are not perfectly transparent. **(b)** Rotating one of the polarizers by 90° blocks virtually all the light from coming through. **(c)** However, inserting a 45° polarizer between the orthogonally oriented polarizers changes the intermediate polarization to 45°, allowing some light to emerge from the final polarizer **(d)**.

polarization, the detector is able to pick up some signal, as you found out in the Figure 13 experiment.

The same exact effects can be studied using polarizing films and visible light. Although 3-cm microwaves are more than four orders of magnitude larger than visible light, they are both electromagnetic radiation and behave in the same way. Polarizing films are very inexpensive, so they allow easy and affordable experimentation with the important concept of polarization. Low-cost, linear-polarizing film is sold by educational and scientific supply companies such as Anchor Optics or Spectrum Scientifics.

Polarized film doesn't usually come labeled for its axis of polarization. However, the axis of polarization is easy to find by looking at sunlight reflecting from water. The glare is almost completely horizontally polarized (although this does depend on the height of the sun). The glare should be minimal when viewed by a vertically oriented polarizer.

Try out the experiment shown in Figure 15. Play around with the film and really try to build an instinctive understanding of polarization and polarizers.

REAL-WORLD BEHAVIORS

As you collect data, remember that Gunnplexers, stripboards, and other microwave components do not behave exactly as do their ideal, theoretical counterparts. For example, data from real Gunnplexers approximate, but do not exactly lie on, the ideal curve of Figure 13b. You should also have observed that stripboards are far from ideal polarizers, since they attenuate the microwave beam, even if they are perfectly oriented with respect to the polarization of the transmitter/receiver system. In addition, real-world polarizers also reflect a part of the beam, allowing "standing waves" to be formed at certain positions within the path between the Gunnplexers.

Conduct the experiment shown in Figure 16. Place the transmitter and receiver horns end-to-end, and then *slowly* move the units apart. Since the microwave horns are not perfect transmitters or receivers, they act as partial reflectors. As such, some of the

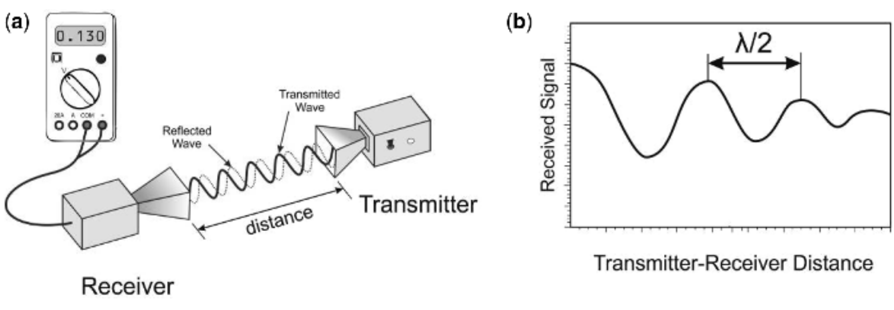

Figure 16 The microwave horns act as partial reflectors, so that the radiation from the transmitter reflects back and forth between the transmitter and the receiver **(a)**. **(b)** The transmitted and reflected waves will be in phase whenever the distance between the transmitter and the receiver is an integer multiple of $\lambda/2$, peaking the signal at the receiver.

radiation from the transmitter reflects back and forth between the transmitter and the reflector. However, if the distance between the transmitter and the receiver is an integer multiple of $\lambda/2$, then all the multiply-reflected waves entering the receiver horn will be in phase with the primary transmitted wave. Under this condition, the primary transmitted and reflected waves will be in phase, peaking the received signal.

Record the distance every time you find a maximum signal as you slide the units apart. How well are you able to calculate the signal's wavelength and frequency using this method? Compare it to the specified operating frequency of your Gunnplexers (X-band Gunnplexers commonly found in microwave door openers and radar speed guns operate at a frequency of 10.525 GHz, which has a wavelength of 2.85 cm.)

Play with your Gunnplexer setup so that you uncover its idiosyncrasies. For example, see how placing your hand close, but not in the way of the beam, affects your readings. What about sweeping the receiver away from the direct line between the antennas facing each other? Go ahead—try it out! You will find out that the microwave beam is not a pencil-tight beam like that of a laser pointer, but rather fits a rather wide Gaussian distribution.

Understanding the equipment is always an important step in the design of an experiment, since real-world components rarely behave in the same way as their theoretical counterparts. The various glitches and artifacts in data due to real-world behaviors in your equipment may completely obscure the effect that you are trying to measure. Even worse, sometimes these peculiarities trick you into believing that they are the very signal that you are trying to measure.

DOUBLE-SLIT INTERFERENCE WITH MICROWAVES

A double-slit experiment with 3-cm microwaves will give you the basic understanding of how double-slit experiments are conducted in sophisticated quantum research that we will discuss in chapters 7 & 8. Just as so many of the other specialized particle detectors, the Gunnplexer receiver does not produce an image, so the interference pattern needs to be measured one point in space at a time. Observing the double-slit interference with the Gunnplexers requires the receiver to be scanned along the plane where the interference pattern is formed.

You will need to build a *goniometer stand* to conduct this experiment. The stand has two guide rails joined by a pivoting joint, with a protractor to measure the angle between the arms. We built ours (Figure 17) from 1-in. × 1-in. cross-section, T-slotted aluminum extrusions made by 80/20, Inc. We joined two 60-cm-long extrusions using a digital protractor made by iGaging. These are commonly sold by woodworking tool suppliers to enable accurate setting of table-saw blade and fence angles. We built two Gunnplexer unit holders from 80/20, Inc. L-brackets and 4-hole plates. We tapped a $\frac{1}{4}$-in. hole in the back of the boxes we used to enclose the Gunnplexers, and used a knob screw to hold the units at any angle we require. A stick-on metric tape and two stick-on protractor dials complete our goniometer mount.

Make a slide holder out of sheet metal or a thin metal sheet that you can easily bend. Place a strip of adhesive-backed magnetic tape where the various slits and slides will be mounted. The plane for slide mounting should be centered on the

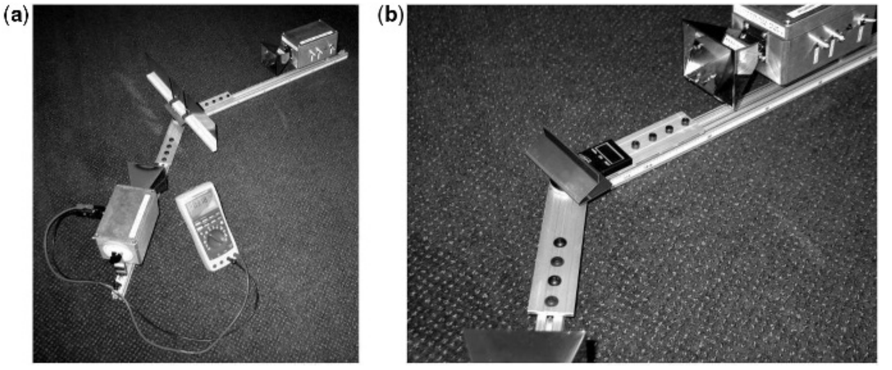

Figure 17 Our homemade goniometer stand is built from two pieces of 80/20, Inc. aluminum T-slot profile joined by a digital protractor. **(a)** Stick-on rulers and protractor dials make it easy to position the Gunnplexer units. **(b)** A folded sheet-metal holder with magnetic-tape backing supports slides right over the pivot point.

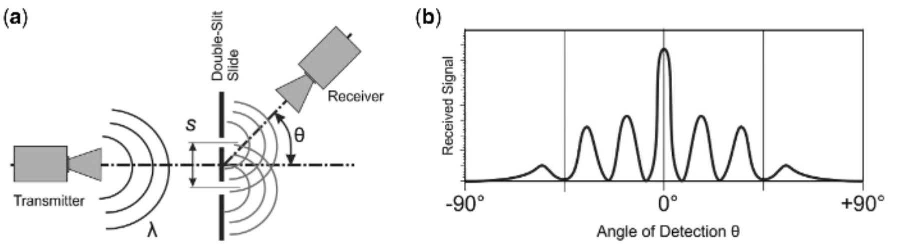

Figure 18 Many experiments to observe the quantum behavior of particles use a nonimaging detector mounted on a goniometer stand to measure the interference pattern. **(a)** Measuring the double-slit interference with microwaves is an excellent way to prepare for more advanced experiments. **(b)** With this geometry, peaks in the interference pattern are found at integer multiples of $s(\sin\theta) = \lambda$.

protractor's axis. Cut two double-slit slides out of sheet metal (or any other metal that sticks to a magnet). Make one spacer have a 6-cm-wide slit spacer, and the other a 9-cm-wide slit spacer. Make the slits 1.5-cm wide. Use a wooden dowel to keep the slotted slide straight.

Scan the receiver around the double-slit slide as shown in Figure 18a. You should find that the location of interference fringes as a function of the angle of detection is dependent only on the wavelength λ, and the center-to-center distance between the slits s. As the goniometer arms are moved, the received signal should peak at integer multiples of $s(\sin\theta) = \lambda$, as shown in Figure 18b.

THE DOPPLER EFFECT

Lastly, if you built at least one of the units to act as both a transmitter and receiver, you essentially have the heart of a police radar gun, and you may want to experiment with

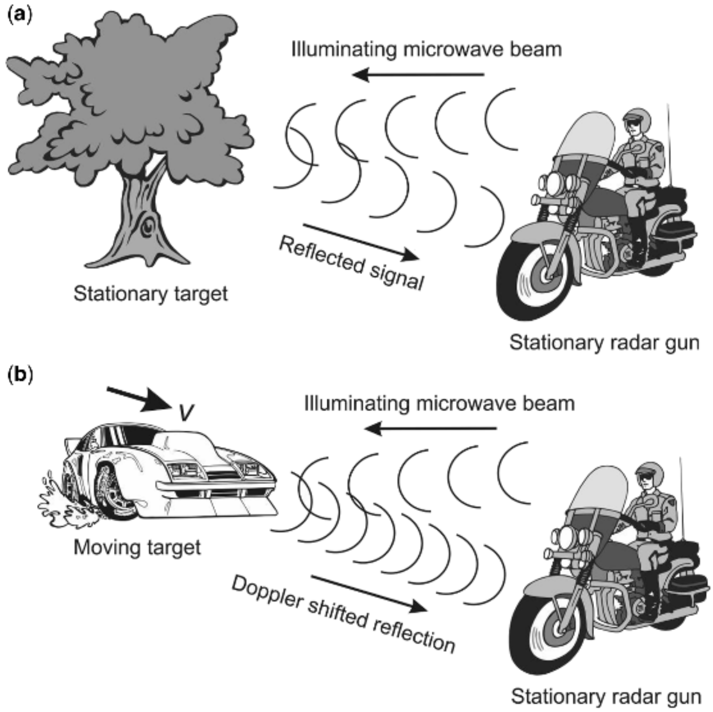

Figure 19 A Doppler radar illuminates its target with a microwave signal of frequency f_t. **(a)** A stationary object simply reflects the signal at the same frequency. However, a moving target shifts the reflected signal by $f_{\text{Doppler}} \approx 2V f_t/c$, where V is the relative velocity between the moving target and the radar gun, and c is the speed of light.

the interesting wave property of light called the Doppler effect. Connect the Gunnplexer's detector diode output (mixer output) to an audio amplifier, such as the microphone input of an old cassette tape recorder.[‡] It is a good idea to place a 1-μF nonpolar capacitor between the Gunnplexer's output and the audio amplifier's input to get rid of any DC currents. Turn on the transmitter and point it at a passing car. The whooshing sound that you will hear is the Doppler shift caused on the reflected microwaves by the car's movement.

Take a look at Figure 19. The signal reflected by a stationary object illuminated by microwaves from the policeman's stationary radar gun is of the same frequency as the source. No "beat" tone is generated when the transmitted and received frequencies are subtracted by the Gunnplexer's mixer diode. However, a moving object reflects a signal with frequency shifted in proportion to its speed relative to the stationary source. In this case, the mixer diode within the Gunnplexer reproduces the

[‡]A convenient, self-contained high-gain amplifier and speaker is sold by RadioShack for around $15 as their model number 277-1008.

Doppler shift, and a microcomputer inside the radar gun can calculate the target's speed using the approximation:

$$f_{\text{Doppler}} \approx 2V\frac{f_t}{c}$$

where f_{Doppler} is the Doppler shift, V is the relative velocity between the moving target and the radar gun, f_t is the frequency of the illuminating microwave beam, and c is the speed of light. When using a 10.5-GHz Gunnplexer, the Doppler shift for a car moving at 65 MPH (29.0576 $\frac{\text{m}}{\text{s}}$) will be:

$$f_{\text{Doppler}} = 2V\frac{f_t}{c} = 2 \times 29.0576\left[\frac{\text{m}}{\text{s}}\right] \times \frac{10.5 \times 10^9\,[\text{Hz}]}{299{,}792{,}458\left[\frac{\text{m}}{\text{s}}\right]} = 2035\text{ Hz}$$

which is well within a human's hearing range. For each mile per hour of target speed, the Doppler shift will be equal to approximately 31.3 Hz.

The reason for the shift in frequency is that, as the target approaches, each successive wave has to travel a shorter distance to reach the target before being reflected and detected. The returned waves are essentially compressed in the direction of travel, and the distance between wave crests decreases, thus decreasing the wavelength and increasing the frequency.

If the radar is directed toward a target that is moving away, exactly the opposite situation occurs: each wave has to move farther, and the distance between wave crests increases, thus increasing the wavelength and decreasing the frequency. In either situation, the Gunnplexer generates the same beat tone for a certain velocity, whether the target is approaching or receding.

EXPERIMENTS AND QUESTIONS

1. Place an IF-508 diffraction mosaic slide at a distance of 1 m away from a sheet of white paper placed on the wall, as shown in Figure 4a. Using laser pointers of different wavelengths, measure the fringe separations of the interference pattern produced when the beam passes through the double-slit separations of s =4.5, 5.8, 7.5, and 10 μm. How well do your measurements agree with $d = \lambda r/s$? How does the wavelength of the laser affect your ability to measure the fringe distance? Explain.
2. Replace the IF-508 in the prior setup by a human hair. Using laser pointers of different wavelengths, measure the fringe separations of the interference pattern produced when the beam passes through the hair. Calculate the thickness of the hair. Try thinner and thicker hairs. If available, try a spider web filament. How does the thickness of the hair affect the interference pattern? What combination of wavelength and hair thickness gives the widest fringe separation? Explain.
3. Set up the Gunnplexer units as shown in Figure 16. Measure the received signal, and then reposition the Gunnplexers to increase the distance between the units by 5 cm. Do this for distances between 20 and 60 cm (or more if your setup allows it). Do your data support the idea that the Gunnplexer's detector is sensitive to the intensity I of the electric

field, which falls in proportion to the inverse of the square of the distance ($1/r^2$) between the transmitter and the receiver? Explain.

4. Place the receiver and transmitter on a goniometer stand so that they face each other at a distance of around 50 cm, with the pivot point exactly midway between them. Take a reading of the received signal strength, and then change the angle between the arms by 5°. Sweep the arm to obtain measurements between -90° and $+90^\circ$. How tight is the microwave beam? How well does it match a Gaussian distribution? Explain.

5. Place the receiver and transmitter on a stand so that they face each other at a distance of around 50 cm. Take a reading of received signal strength, and then rotate the receiver to change its polarization angle by 5°. Continue to rotate the receiver to obtain measurements between -90° and $+90^\circ$. How does relative polarization affect the intensity of the detected signal? Does the intensity as a function of polarization follow a smooth curve? Explain.

6. Set up the Gunnplexer units as shown in Figure 16. Measure the received signal when $r = 0$ and then *slowly* move the Gunnplexers away from one another. Record the distances at which the signal peaks and dips out to around 20 cm. Calculate wavelength by measuring the distance between successive peaks (or successive dips), which should equal $\lambda/2$. What is the frequency $f[\text{Hz}] = c/\lambda[\text{m}] = 3 \times 10^8[\text{m/s}]/\lambda[\text{m}]$ at which your Gunnplexer is transmitting? How well does the calculation of frequency based on the average of your measurements compare to the specified frequency for your Gunnplexer? Explain.

7. Place the receiver and transmitter on a stand so that they face each other at a distance of around 50 cm. Rotate the receiver 90° away from the transmitter's axis of polarization. The signal at the receiver should drop close to zero. Insert a polarizer at 0°, 45°, and 90° referenced to the transmitter's polarization. How can inserting the polarizer at 45° increase the signal level at the detector?

8. Take three pieces of linear-polarizing film and look at the reflection of low-angle sunlight from a water surface with each one. Rotate each piece of film until reflections are minimized. Mark the vertical axis on each slide as its axis of polarization. Try the Figure 15 experiment with your labeled pieces of polarized film. Do your results agree with Figure 15? How does rotating one of the pieces of film in Figure 15a and Figure 15c change the amount of transmitted light? Explain.

9. On a clear day, look at different portions of the sky with a piece of polarizing film. Are any areas polarized? What is the polarization of light reflected from pavement? Explain your results.

10. Look at a pair of polarized sunglasses through one of your labeled pieces of polarizing film. What is the axis of polarization of the lenses in the sunglasses? Check out other sunglasses. Are they all polarized in the same orientation? Why do you think sunglasses are polarized in this way?

11. Polarizing film acts as a chemical version of the wire grid. Instead of long, thin wires it uses long, thin polyvinyl alcohol molecules that contain many iodine atoms. These long, straight molecules are aligned almost perfectly parallel to one another, with electrical conductivity provided by the iodine atoms. Examine a polarizing sheet very carefully. Can you see a pattern that resembles a wire grid? Would it be visible under a light microscope? Explain.

12. Place the receiver and transmitter on a goniometer stand so that they face each other at a distance of around 50 cm, with the pivot point exactly midway between the receiver and transmitter. Place a double-slit slide with $s = 75$ mm over the pivot point, as shown in Figure 18. Take a reading of received signal strength at $\theta = 0^\circ$, and then change the angle between the arms by 5°. Sweep the arm to obtain measurements between -90° and $+90^\circ$. Repeat, using a double-slit slide with $s = 105$ mm. Plot your data, and identify the angles at which the peaks and dips of the interference pattern occur. Are successive peaks (or successive dips) separated according to $\sin\theta = \lambda/s$? Explain.

13. Connect the Gunnplexer's detector diode output (mixer output) to an audio amplifier. Point the Gunnplexer at a passing car and pay attention to the whooshing sound that you will hear. How does the Doppler sound produced by the Gunnplexer from an approaching car compare to the sound produced when the Gunnplexer is pointed at a receding car? Explain.