Chapter 1

The Basics

In this chapter, the nature of light is described, as are the main characteristics of light observed and used in various applications. These include refraction and reflection, diffraction, interference, scattering, and the interaction of light with matter—emission and absorption.

Waves, Rays, and Photons

Light is described in terms of waves, rays, and photons. Each is a model of light, and each has its advantages and limitations.

Waves

Light travels in waves. Several examples of waves are those in the ocean and the ripples on a quiet pond when a trout rises, as shown[1] in Fig. 1. The ripples (waves) started as the nose of the trout broke water, probably to snare a fly. Then, they spread outward as a pattern of highs and lows in the water. We can represent these ripples approximately by a series of circles, as shown in Fig. 2. Each solid line represents a maximum in the circular wave. Each dashed line represents a minimum. We have to imagine the slopes in between. If we take a cut through these circular waves, the profile, shown in Fig. 3, looks like a series of maxima and minima. One can generate waves by tying a rope to a tree or other solid object and holding the other end. The waves are generated by moving your hand up and down fairly rapidly, or by moving it side to side. The frequency of the wave is a measure of the

Figure 1 Trout waves.

[1] Marinaro, V., *In the ring of the rise*, Nick Lyons Books, 1976

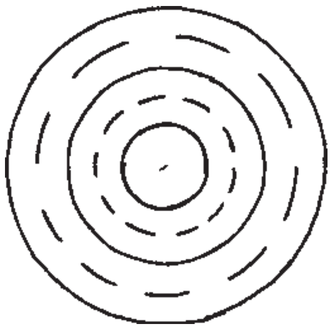

Figure 2 Representation of Circular Waves

rapidity with which you move your hand. The wavelength is a measure of the distance between the peaks in the wave. The direction of the wave, often called the polarization, is determined by whether you move your hand vertically or horizontally, or in some other direction. It could be at any angle or even in a circular or elliptical motion.

The profile of an idealized wave is shown in Fig. 3. This is a wave of five cycles. A *cycle* is the distance from one part of the wave to the next identical part, for instance from a peak to the next peak. Or a trough to the next trough. This is also called a *period*.

The *frequency* is the number of cycles per second, the unit for which is Hertz, named after the famous physicist Heinrich Hertz. The *amplitude* is the height of the wave above zero. Figure 4 shows two waves, one of which has twice the frequency of the other, shown as the weaker line.

Figure 5 shows two waves of the same frequency but with different amplitudes. The wave shown as the heavy line has twice the amplitude of the other. The amplitude is one-half the peak-to-peak value.

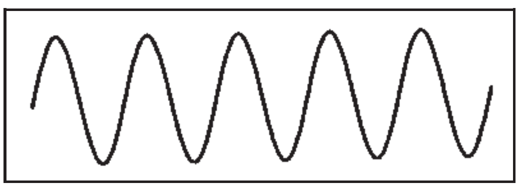

Figure 3 Wave Profile

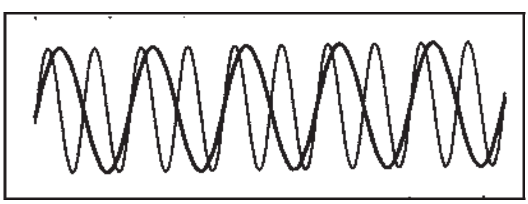

Figure 4 Frequencies

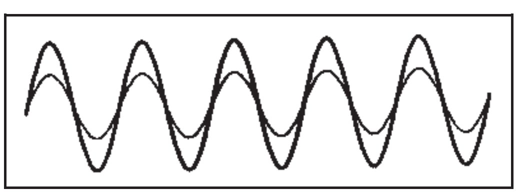

Figure 5 Amplitudes

Another characteristic of a wave is its *phase*. Phase refers to a particular position in the period of the wave. It could be a point right at the beginning (zero phase) halfway through (half phase) or any other position that can be described as a fraction or a percentage of full phase. Two waves can start in phase if their starting points are the same, or they can be out of phase by some amount if they start at different times or in different places.

Light is called an *electromagnetic wave*, and is part of a continuum of such waves, which are generated by the periodic motion of a charge, much like the motion with the rope. Some other waves with which you may be familiar are radio and television waves that provide us information and entertainment. In both cases, as electrons oscillate in the antenna of the transmitter, they set up electric fields that cause electrons to oscillate in the receivers at our houses. They will have the same sort of oscillations and therefore represent the signals we receive.

The electromagnetic spectrum runs from the very high frequency (VHF) gamma and X-rays through ultraviolet, blue, orange, and red to infrared, millimeter waves, microwaves, television, radio, very low frequency (VLF), and ultra low frequency (ULF). Figure 6 shows how these all are arranged by frequency; the next by wavelength. AM radio ranges from about 600 kilocycles per second (kilohertz) to 1600 kHz. FM radio is at higher frequency, from about 90 to 110 megahertz, about 150 times higher in frequency and shorter in wave length. Recall that AM radio is relatively unaffected by hills and mountains, while they can block FM radio waves. The AM waves are much larger, about 1000 feet long. The longest waves used for communications are the VLF or very low frequency waves. They are used by submarines, which trail wire antennas on the surface for secure communications. The

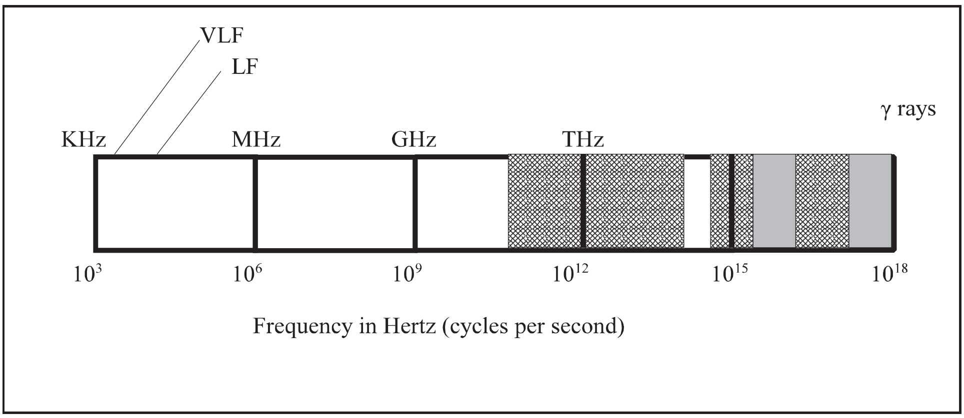

Figure 6 The electromagnetic spectrum on a frequency scale

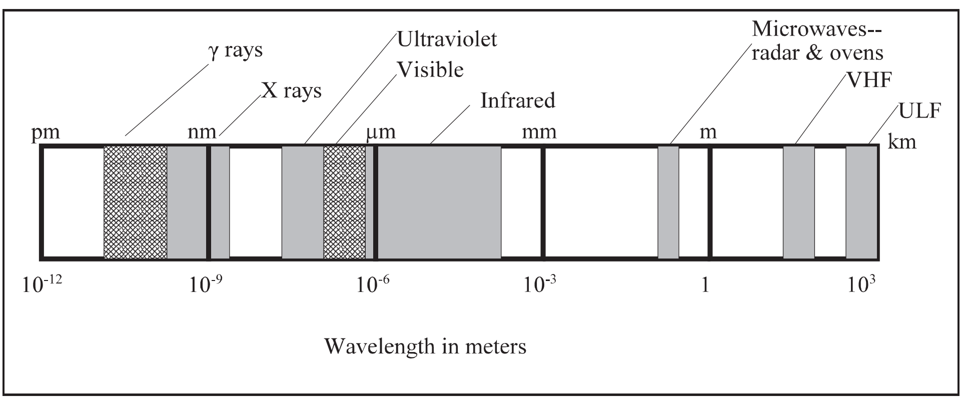

Figure 7 The electromagnetic spectrum on a wavelength scale

Chapter 2

Components and Instruments

Most people are familiar with very basic optical components like mirrors, lenses and prisms. Some of their characteristics may not be so familiar, and certainly the operation of more complicated instruments like telescopes, microscopes, and spectroscopes are not as well known. Even more exotic are such devices as interferometers, lasers, detectors, and fiber optics. These are all described here, along with a few more.

Mirrors

Mirrors reflect light. They are often a blank, a plate of solid material, that is covered with a highly reflecting film, as shown in Fig. 1. The blanks are made of glass, sometimes metal and even plastics or composites. They can have the reflecting coating on either the front or the back surface if the blank is transparent. They can be plane (flat) or curved.

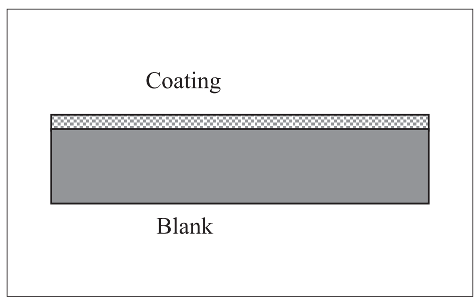

Figure 1 A typical mirror

Mirrors have been used for a very long time. There are records that obsidian mirrors were used in Turkey about 7500 years ago. Mirrors were first *reflectorized* (commonly called silvered) by Justus von Liebig. The modern practice uses tin, silver, gold, or aluminum. Any metal including copper, can provide the reflection, although a colored reflection will then be generated.

Plane Mirrors

These have smooth, even, planar surfaces, and are most often used as vanity mirrors. We use them to shave and apply cosmetics. They seem to reverse images from left to right but not from up to down. Full-length mirrors are useful to make sure your slip is not showing and that your shoes are shiny. Ask yourself how big a mir-

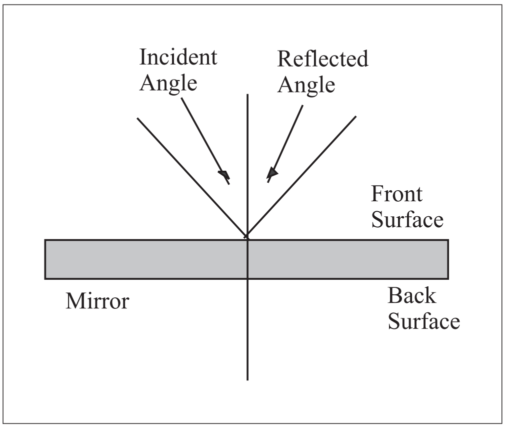

Figure 2 Plane mirror geometry

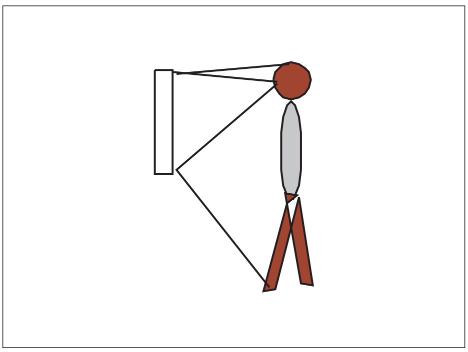

Figure 3 A full-length mirror needs to be only half height

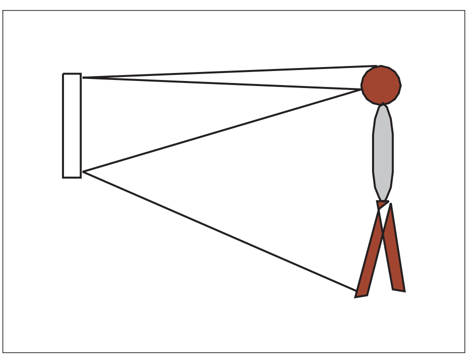

Figure 4 The distance makes no difference

ror has to be to give a full-length image. Does it depend upon how far you are from the mirror? Think about it before you read on.

Before we answer that question, let us review the basic law of reflection. A plane mirror reflects light according to the law of reflection: the angle a reflected beam or ray makes with the surface normal is the same as the angle it makes upon incidence. This is shown in Fig. 2.

A mirror that is only half your height is tall enough to provide you with a full-length image of yourself, no matter how far away you are from it. The geometry shown in Fig. 3 shows that a "full-length" mirror need be only half your height. It can also be used to show that the distance you are from the mirror makes no difference.

The figure shows a person standing in front of a mirror. The top of the mirror is halfway between his eyes and the top of his head. A ray from the top of the head to the top of the mirror determines the angle of incidence. The ray will be reflected back to the eye at an angle equal to this. It is this doubling that allows the mirror to be only half the height of the person using it. The bottom is halfway between his eyes and his feet. The next figure shows the same person about twice as far from the mirror. The mirror is the same size; the angles are smaller. Reflections are shown from the front surfaces for simplicity

An interesting application for a plane mirror is to view a baby placed rearward in a car seat in the rear seat of the car. Hindsight, by Blue Ridge International Products, is a gaily decorated, large mirror that attaches to the top of

The Planets

They do not radiate of themselves, but reflect the sun's light. Although it is hard to tell with the naked eye, the planets subtend a larger angle than the stars. A good telescope will let you see the rings of Saturn and the canals on Mars, but gives no structural information about stars. The fact that planets do subtend larger angles means that they are less affected by the atmospheric turbulence. In a sense, they average it out. Thus, you can usually tell a star from a planet by its degree of twinkle, and, of course, some of them are very bright.

The Sky, Sunrise, Sunset

Here in Arizona we have beautiful, deep blue skies almost every day of the year. Why are they so blue? The simple answer is scattering. Light is scattered by the molecules and small particulates in the atmosphere. These particles are less than a micrometer in size, more or less spherical and floating in the air. They scatter different colors of light differently. The shorter wavelengths, the blues, are scattered more than the longer ones, the reds. This is because the particle, relative to the wavelength of the light, is larger for a shorter wavelength. Thus, the sunlight that is essentially white light is scattered to us more in the blue than in the red, and we see a blue sky away from the sun.

As I wrote this on September 7, 2003, I paused to listen to National Public Radio (NPR) explain the blue sky. They said it is because blue light is more energetic than the other colors and therefore bounces more. They added that this was the explanation of Rayleigh. Well, it is true that blue photons are more energetic than the longer-wavelength photons, and the argument is not wrong, but I think it is not quite right, either, and I am sure that was not Rayleigh's explanation! He was the master of waves, and photons were not discovered until 1905.

The history of the explanation of the blue sky goes back to an Arab, Aby Yusuf Yaquib ibn Ishaq al-Sabbah Al-Kindi, who lived about 800 AD. He thought that the blue sky was a mixture of the darkness of the night plus the sunlit particles of haze. Leonardo da Vinci attributed the blue color to scattering of sunlight by minute water particles. Other famous physicists, such as Isaac Newton, Pierre Bouguer, Dominique Arago, and John Tyndall, continued to believe that the blue color came from scattering from minute water droplets. Then, in 1871, John William Strutt, the third Baron Rayleigh, showed that it was scattering from molecules, and that the scattering from particles smaller than the wavelength of light is inversely proportional to the fourth power of the wavelength. Blue light of about 400 nm scatters about sixteen times as much as red light at 800 nm.[2]

As you can see in Figure 3, the sky is especially blue, in this case, away from the sun. The scene is near my home, viewing the Catalina Mountains to the north.

[2] Lilienfeld, P., "A Blue-Sky History," *Optics and Photonics News*, June 2004.

Figure 3 An Arizona blue sky

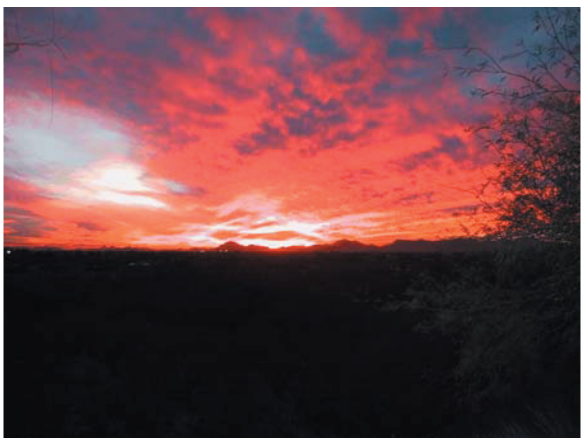

Figure 4 An Arizona sunset

As the sun sets, and as it rises, too, it sends its light to us along a path that is close to the horizon. The reds are scattered less, so they get through this long atmospheric path better than the blues. So we get red sunsets (and sunrises), and they are redder if there are more particles in the path, as with some clouds.

Clouds

These are white, black, and shades of gray. The particles in clouds, nascent water droplets, are bigger than the particles in the clear sky. They scatter all wavelengths equally. If there is not too much water, the droplets scatter all colors of light in all directions and the clouds look white. If they are bigger, and therefore have more

Chapter 4

Applications

This chapter is a collection of optical applications I have gathered for more than ten years. They range from some very simple detectors for security to complex devices to control manufacturing processes, aircraft, and rockets. I have divided them into various categories to provide some organization, but they could just as well have been presented in a different order. There are surely more optics applications in our lives, but these are all I have found or remembered.

Aerospace

This section groups applications that are nonmilitary in nature but are part of our aeronautics and space applications and ventures. Many of the applications and instruments have been developed by the National Aeronautics and Space Agency (NASA).

The Laser Gyroscope

As many readers already know, the gyroscope has long been a part of the navigational equipment of aircraft. Familiar, mechanical versions consist of two or more spinning members that react to external forces. These reactions are monitored and used to show when the aircraft begins to veer off course. When the vehicle, usually a plane, turns from the direct-line path it was sent on, the gyros sense the acceleration in the different direction, and make a correction to the course. Lasers have been used to replace these "iron" gyros, and they have been far more accurate, more compact, and even less expensive.

A laser, with its very narrow spectral band of light, is directed into a Sagnac interferometer. Recall that this interferometer has a beam that is split and then has two beams that rotate clockwise and counterclockwise respectively. They then combine and interfere. If there is no rotation of the interferometer, there is constructive interference, but if there is rotation, there is a frequency shift in the opposite directions because of Doppler effect. Thus any tendency to go off course is sensed by the rotation of the laser gyroscope. This is a very sensitive measurement, and these laser gyros have better performance than the old spinning gyroscopes.

The Fiber Optic Gyroscope[1]

The fiber optic gyro is similar to the laser gyro, but is even more compact and less expensive. These instruments have appeared on Boeing 777s, Dormier commuter aircraft, remotely piloted helicopters, lawn mowers, and shopping-mall floor scrubbers. An accuracy of 0.00038 deg. per hour has been demonstrated. This means that on a cross-country airline flight taking five hours, the direction will be off by 0.0019 deg. or 33.16 microradians, and therefore 0.099 miles or 525 feet. The flight from New York to Los Angeles should not miss the airport!

One example is a high-sensitivity I-FOG, or Interferometric Fiber Optic Gyroscope, that can obtain an accuracy of 0.15 deg. per hour with a coiled loop that is 10 cm in diameter, 1 km long and uses light of 1550 nm. The coil consists of approximately 30 loops.

Almost monochromatic light from the source is passed through a beamsplitter and polarizer to a spatial filter, consisting of two lenses and a pinhole. Then it enters the coil via a beamsplitter, which causes the two different beams to propagate in different directions. They pass through the entire coil and emerge, where they are recombined by the beamsplitter, spatially filtered again, and go to the detector, which senses the degree to which they are out of phase. Other schemes have been devised that make use of a variety of different solid state beamsplitters and combiners. The devices can operate with sensitivities ranging from 0.001 deg. per hour to 100 deg. per hour.[2]

Check-In Safety System[3]

Several airlines have implemented a face-recognition system to ensure that passengers and their luggage agree. A lipstick-size camera takes a digital photograph of the person who checks a bag. The image is embedded on a smart-card that is used both as a boarding pass and a baggage check. During the boarding process, every passenger is checked. The recognition system must find the facial image anywhere in the field of view in a variety of orientations. It also ignores hair length and facial hair and concentrates on several unique features. It operates in the ambient light of an airport. This ensures that every person who checked a bag is on the plane. It does not prevent the suiciders who will get on the plane.

Hot Air Gas Detection

At the Stennis Center of NASA, where there are many rocket pads, one concern is small hydrogen flames that can cause much larger flames and even explosions. A

1 Tebo, A., *OE Reports*, 158, February 1997

2 Burns, W., "Fiber Optic Gyroscopes–Light is Better," *Optics and Photonic News*, May 1998

3 Mendonsa, R., "Face-Recognition Technology Makes Air Travel Safer," *Photonics Spectra*, 20, September 1997

hydrogen flame is essentially invisible to the human eye and to visible cameras and TVs. So a system has been developed to detect these small flames in the infrared. The system uses a zoom lens in the front, followed by a beamsplitter that directs the visible light to a standard three-color CCD. The other beam is then split into two infrared wavelengths, one at 2.7 µm to detect the emission from heated water molecules in the flame, the other at nearby but different wavelengths to get the background. The background image is subtracted from the flame image and the result is processed. The flame can then be displayed as red (or some other color) superimposed on the standard color image.[4]

In related research, I investigated a way to detect the flames but prevent similar, much larger, hydrogen flames from rockets taking off or being tested from interfering, from creating false detections. This enabled the detection of small hydrogen flames that should not be there on gantries that are nearby, while preventing false alarms from real flames from distant gantries. The basic technique is to pick wavelengths in which the flame radiation is highly attenuated by the atmosphere. This requires carefully adjusting the spectral band on the edge of the line emission of the water molecules. It worked on paper, and it has never been published, but it was reported to Stennis.

The Red Planet

At the dawn of 2004, we landed a rover on Mars to explore its composition, history, and the possibility (probability) that life was ever there. It is loaded with optical instruments. It has a microscopic imager on an arm out front. It has navigational cameras on a four-foot pedestal. It is powered by solar arrays. It has high-resolution panoramic cameras and two different kinds of spectrometers.[5]

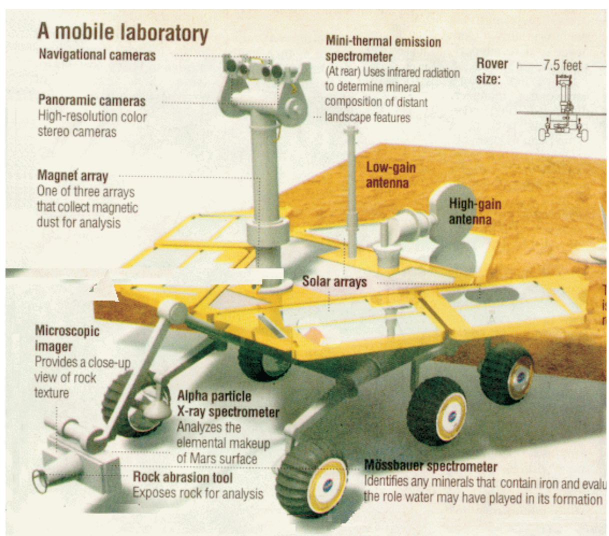

Figure 1 Caption

The orbiting mother ship kept track of the lander with an arrangement of laser diodes and a CCD camera. It sent the laser beams to an array of retroreflectors on the lander and used the

[4] "Camera Images Hydrogen Fires in Three Wavelength Bands," Stennis Space Center, *Photonic Tech Briefs*, July 1999

[5] Adapted from Stauffer, T., "Back to Mars," *The Arizona Daily Star*, Jan. 4, 2004