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.

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 in Fig. 1. The ripples (waves) start as the nose of the trout breaks 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]

1 Marinaro, V., *In the Ring of the Rise*, Nick Lyons Books, 1976. (Image courtesy of Random House/Crown Publishing, copyright 1976.)

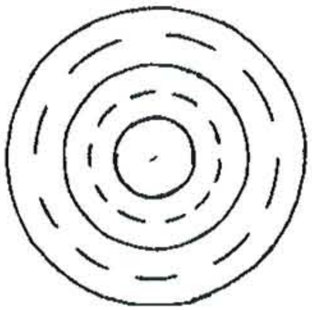

Figure 2 Representation of circular waves.

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 one peak to the next peak, or one 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.

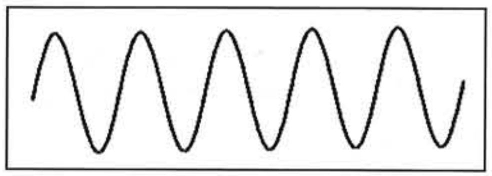

Figure 3 Wave Profile.

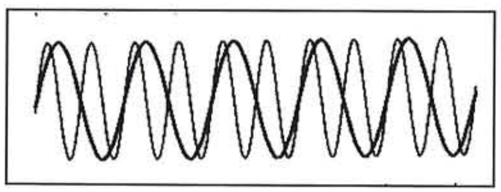

Figure 4 Frequencies.

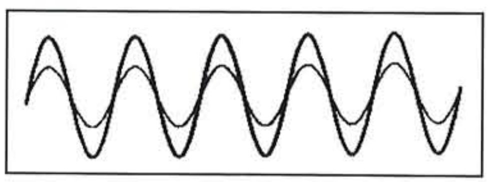

Figure 5 Amplitudes.

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 elec-

trons oscillate in the antenna of the transmitter, they set up electric fields that cause electrons to oscillate in the receivers at our houses. They 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; Fig. 7 by wavelength. AM radio ranges from about 600 kilocycles per second (kilohertz or kHz) to 1600 kHz. FM radio is at higher frequency, from about 90 to 110 megahertz (MHz), which is about 150 times higher in frequency and shorter in wavelength. 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. Figures 6 and 7 show the regions

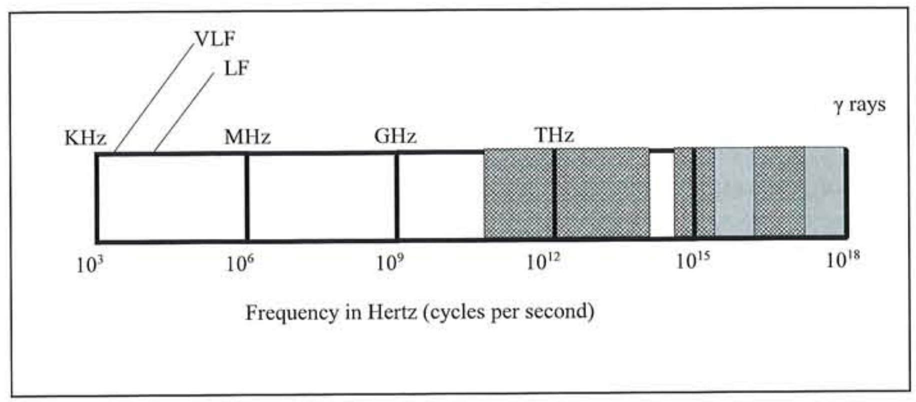

Figure 6 The electromagnetic spectrum on a frequency scale.

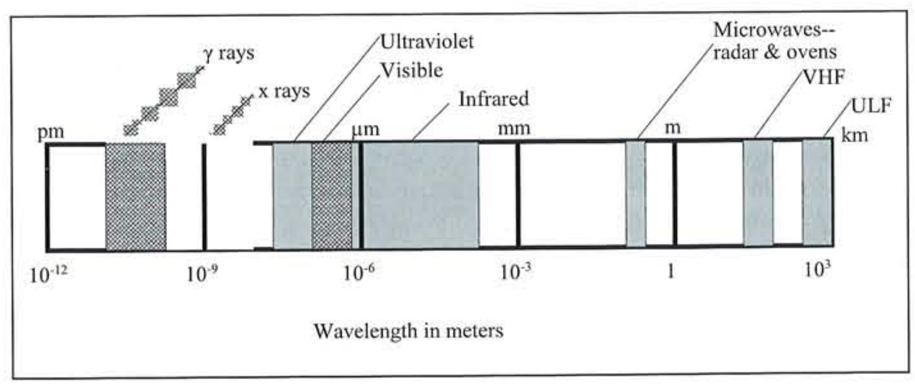

Figure 7 The electromagnetic spectrum on a wavelength scale.

approximately to give an idea of the entire range of the electromagnetic spectrum. I have intentionally given frequencies in several different ways.

Coherence

Laser light is coherent, and the coherence is especially important in communication by light waves. The word *coherence* means "go together," just as *cooperate* means "operate together." It means that the waves continue to travel together. The two waves with the same frequency shown in Fig. 5 (the amplitude example), go together. The peaks of both occur at the same place and so do the troughs and the zeroes. The only difference is the height.

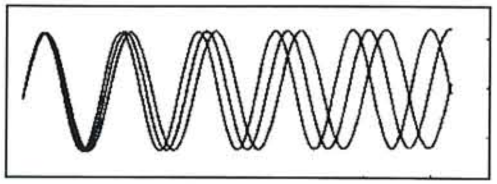

Figure 8 Incoherence from different frequencies.

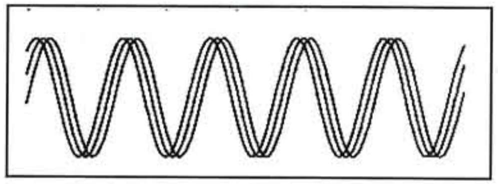

Figure 9 Incoherence from different timing.

There are two ways in which two or more waves do not go together, that is, are not coherent. One is if the waves start at different times, and the other is if they are of different frequencies. Figure 8 shows how the waves gradually get out of synchrony if they start at the same time, but are of slightly different frequencies. Notice that they start in synch, but in about five cycles the maximum of one is about where the minimum of the other occurs. They are out of synch. So one requirement for light to be coherent is that it must be essentially monochromatic (the same color) and the same frequency. The distance over which they are still in reasonably good synchronization is called the coherence length. If the waves are monochromatic but do not all have the same time of generation, their combination will not be coherent. Figure 9 shows how this is with a few waves. As more and more waves are added, starting at different times, there will be peaks at all points and troughs at all points, and the concept of a monochromatic wave is completely blurred. The waves do not become increasingly out of phase as they go to the right as do the waves that consist of several frequencies; they are incoherent from the beginning.

Rays

Rays are straight lines that represent the direction of waves. They are a simpler model than either waves or particles. Figure 10 shows that rays are just lines perpendicular to a wavefront. The wavefront, naturally enough, is just the front of the expanding wave. It is so much easier to design lenses and mirrors and other instruments using straight rays rather than invoking all the characteristics of either waves or photons. When these circular waves expand enough, the wavefronts become straight lines. In three dimensions, the spherical wavefronts become planes. Spherical waves are related to object and image points at finite distances. Plane waves relate to infinite objects and images.

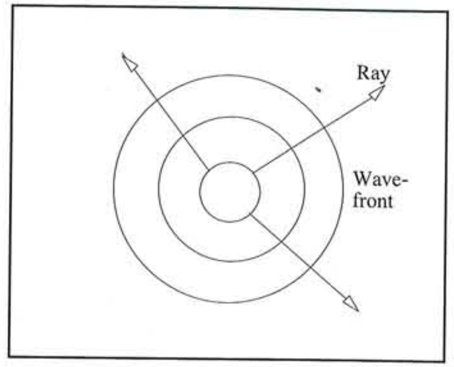

Figure 10 Waves and rays.

Beams

Perhaps the most intuitive description of light propagation is in terms of beams. Turn a flashlight on and a beam of light emanates from it. This is a *divergent beam*, as shown in Fig. 11. The farther it goes, the wider it gets. If you look at it from the other end, it is a *convergent beam*. In a convergent beam the light converges to the point of the cone it makes. Lenses usually generate convergent beams. Divergent beams of light radiate from a point. These are also called pencils of light, in analogy to the point of a wooden pencil. The third type of beam is *collimated*, one that neither diverges nor converges but has the same diameter throughout its entire length. One can never attain a truly collimated beam, but it is a useful approximation and fiction.

These beams can be thought of as consisting of many rays. In particular, the marginal rays would be the outside lines that bound the beams. Ray optics is most useful in the design of lenses, mirrors, prisms, and other such optical components.

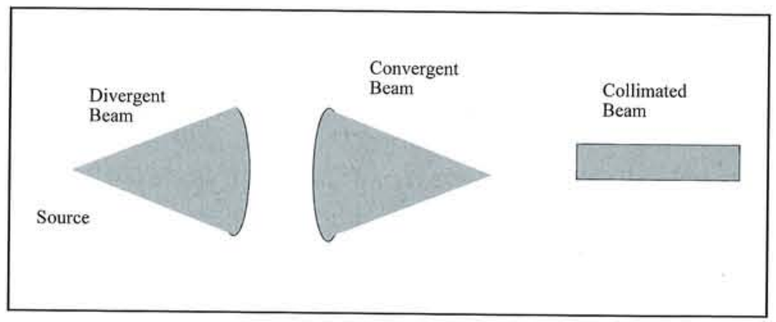

Figure 11 Beams.

Photons

Photons may be regarded as small bundles, clumps, or particles of light. The existence of photons started with the work of Max Planck, who explained the spectrum of blackbody (idealized) radiation by assuming the energy in the material was quantized. There was not a continuum of different energies, but there were jumps. In today's world we would say *digitized*. Planck refused to believe that the light was quantized, that it came in specific, separate clumps of energy. It was Albert Einstein who determined this by his explanation of the photoelectric effect. By the way, it was for this, not his monumental work on relativity, that he was awarded the Nobel Prize.

Duality

So light is described either as a wave motion or as a conglomeration of particles. Light has both properties. Remarkably, so do other particles. Electrons have wavelike properties. In fact, everything has both particulate and wavelike properties. The bigger the particle, the less wavelike it is. That is why we do not think of a baseball as a wave (although some poor hitters may). Some of the ways in which light reacts with matter are best described in terms of photons, and some should be described in terms of waves.

The Conundrum

A number of experiments have been carried out to learn just what a photon really is. One of these uses two slits. Light is shined on the slits, and the pattern behind them is observed. Classically, assuming that light is a wave motion, the pattern should be sinusoidal (like the waves in the illustrations above). The photon explanation then is that the photons follow a probability that sends them into a pattern that is the same as that predicted by the wave theory.

But then the conceptualizing gets more and more difficult. Shine one photon on the double slit. It must go through one slit and not the other. Now shine another after a considerable time has elapsed. It has to go through one of the two slits. The remarkable thing about this is that after many photons have been sent, with considerable time between them, the pattern will be the same!

When a photon goes through one slit, how does it "know" the other one is there? We do not know. But we do know that a photon is not a small clump of localized energy; it is spread out. If we know that a photon is of a particular wavelength, then by the uncertainty principle, we do not know at all where it is.

If this sounds a little weird and a little too complicated for my promised simple explanations, I apologize, but I wanted to make the point that there is great uncertainty in knowing exactly what light is. A fascinating publication[2] at a very advanced level addressed this question. Several of today's foremost theoretical optical physicists addressed the question: "What is a photon?" I will not give you their full answers, but I will give some snippets that capsulize their answers.

2 Roychoudhuri, C., and R. Roy, "The nature of light: what is a photon," *OPN Trends*, OSA, 3, October 2003.

"We will probably never be able to visualize a photon, but we may soon be able to choreograph one; to describe the process rather than the object." This was stated by David Finkelstein of Georgia Tech.

"The particulate nature of the photon is evident in its tendency to be absorbed and emitted by matter in discrete units leading to quantization of light energy." That was expressed by my friend Marlon Scully and his colleagues at the University of Texas (he is now at Princeton University).

In sum, all of these authors describe how the photon behaves as both a wave and a particle, but no one can say what it is.

My favorite description, coming from long-time colleague Stan Ballard, is to think of it as a corrugated hot dog. It has the localization and particality of a hot dog, but it has the wavelike nature of the corrugations. In a letter to the editor following the above-mentioned articles, R. C. Millikan, University of California, Santa Barbara, describes the photon as "a quantum harmonic oscillator with a twist," and even gives his "speculative but serious" picture, as shown in Fig. 12. The photon is traveling in the direction of the arrow and "vibrates up and down and side to side in a spiral sort of motion. It is somewhat localized, but it also has wave properties."

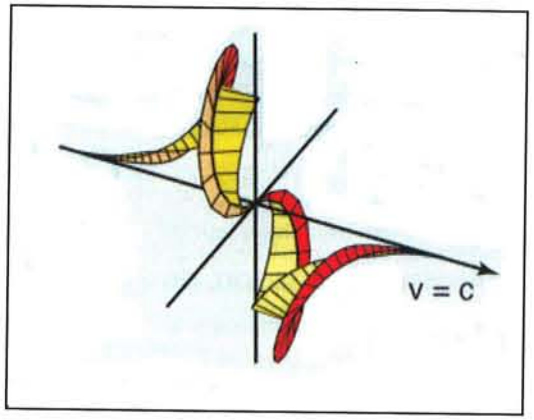

Figure 12 The Photon?[3]

The Practical Solution

Although it is fascinating to read the treatments of these theoreticians in terms of quantum electrodynamics, we do not need to understand it to understand how optical gadgets and optical phenomena work. For understanding almost all instruments, rays are sufficient. For most of the natural phenomena and many instruments, waves provide enough information to understand the interference, diffraction, and scattering effects. Finally, for some of the emission and detection instruments and applications, the particle model is satisfactory.

3 Millikan, R. C., *Optics and Photonics News*, November 2003. (Image courtesy of OSA, copyright 2003.)