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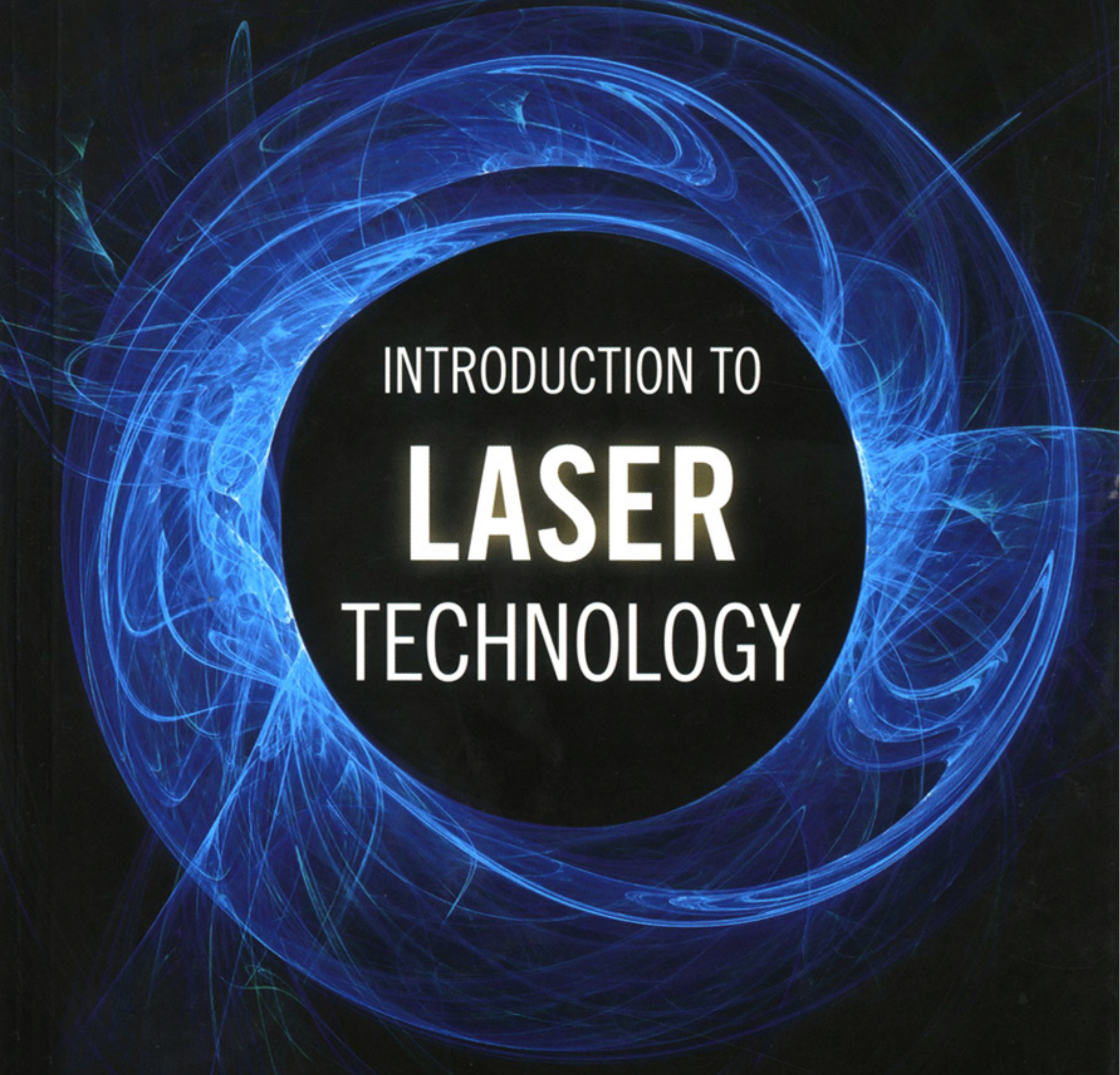

INTRODUCTION TO LASER TECHNOLOGY

C. BRECK HITZ
J. J. EWING • JEFF HECHT

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Introduction to
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Fourth Edition

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Preface

HOW DOES A LASER WORK AND WHAT IS IT GOOD FOR?

Answering this question is the goal of this textbook. Without delving into the mathematical details of quantum electronics, we examine how lasers work as well as how they can be modified for particular applications.

THE BOOK'S APPROACH

You should have some feeling for the overall organization of this textbook before you begin reading its chapters. The book begins with an introductory chapter that explains in unsophisticated terms what a laser is and describes the important applications of lasers worldwide.

Lasers produce light, and it is essential to understand how light works before you try to understand what a laser is. Chapters 2 through 5 are dedicated to light and optics, with lasers rarely mentioned. The subjects discussed in these chapters lead naturally to the laser principles in the following chapters, and the laser chapters themselves will not make much sense without the optics concepts presented in Chapters 2 through 5.

The heart of this text is contained in Chapters 6 through 9 because these are the chapters that explicitly answer the question, How does a laser work? As you read these chapters, you will find that two fundamental elements must be present in any laser: some form of optical gain to produce the light, and some form of feedback to control and amplify the light.

Having covered the fundamentals, the book turns to more sophisticated topics in Chapters 10 through 20. Chapters 10 to 13 describe how a laser can be modified for particular applications. Lasers can be pulsed to produce enormously powerful outputs, or their beams can be limited to a very narrow portion of the optical spectrum. And the color of the light produced by a laser can be altered through nonlinear optics.

Finally, the last seven chapters of the book apply the principles developed in the first 13 chapters to explain the operation and engineering of today's commercial lasers. All important lasers—gas lasers, optically pumped solid-state lasers, fiber lasers, and semiconductor lasers—are explicitly covered in these chapters.

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Earlier editions of this book have been used by one of us (BH) in teaching this material to numerous scientists and technicians over the years. Many of those individuals have made suggestions that have been incorporated into the current version of the text, and we wish to acknowledge the assistance of Professor Joel Falk of the University of Pittsburgh with the original manuscript, and of the late Professor Anthony Siegman of Stanford University for helpful suggestions about explaining the subtleties of quantum mechanics on an intuitive level.

Chapter 1

An Overview of Laser Technology

The word laser is an acronym that stands for “light amplification by stimulated emission of radiation.” In a fairly unsophisticated sense, a laser is nothing more than a special flashlight. Energy goes in, usually in the form of electricity, and light comes out. But the light emitted from a laser differs from that from a flashlight, and the differences are worth discussing.

You might think that the biggest difference is that lasers are more powerful than flashlights, but this concept is more often wrong than right. True, some lasers are enormously powerful, but many are much weaker than even the smallest flashlight. So power alone is not a distinguishing characteristic of laser light.

Chapter 5 discusses the uniqueness of laser light in detail. But for now it is enough to say that there are three differences between light from a laser and light from a flashlight. First, the laser beam is much narrower than a flashlight beam. Second, the white light of a flashlight beam contains many different colors of light, whereas the beam from a laser contains only one, pure color. Third, all the light waves in a laser beam are aligned with each other, whereas the light waves from a flashlight are arranged randomly. The significance of this difference will become apparent as you read through the next several chapters about the nature of light.

Lasers come in all sizes, from tiny diode lasers small enough to fit in the eye of a needle to huge military and research lasers that fill multistory buildings. And different lasers can produce many different colors of light. As we will explain in Chapter 2, the color of light depends on the length of its waves. Listed in Table 1.1 are some of the important commercial lasers. In addition to these fixed-wavelength lasers, several important tunable lasers are discussed in Chapter 20.

The “light” produced by carbon dioxide lasers and neodymium lasers cannot be seen by the human eye because it is in the infrared portion of the spectrum. Red light from a ruby or helium–neon laser, and green and blue light from an argon laser, can be seen by the human eye. But the krypton-fluoride laser’s output at 248 nm is in the ultraviolet range and cannot be directly detected visually.

Table 1.1 is by no means a complete list of the types of lasers available today; indeed, a complete list would have dozens, if not hundreds, of entries. It is also incomplete in the sense that many lasers can produce more than a single, pure color. Nd:YAG lasers, for example, are best known for their strong line at 1.06 μm, but

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Table 1.1. Some important commercial lasers

Laser	Wavelength	Average power range
Carbon dioxide	10.6 μm	Milliwatts to tens of kilowatts
Nd:YAG	1.06 μm	Milliwatts to hundreds of watts
	532 nm	Milliwatts to watts
Nd:glass	1.05 μm	Watts[1]
Diodes	Visible and IR	Milliwatts to kilowatts
Argon-ion	514.5 nm	Milliwatts to tens of watts
	488.0 nm	Milliwatts to watts
Fiber	IR	Watts to kilowatts
Excimer	Ultraviolet	Watts to hundreds of watts[2]

[1] Although glass lasers produce relatively low average powers, they almost always run in pulsed mode, where their peak powers can reach the gigawatt levels. Peak powers are explained at the beginning of Chapter 11.

[2] Excimers, like the glass lasers discussed in the note above, are pulsed lasers, capable of peak powers in the tens of megawatts.

these lasers can also lase at perhaps a dozen other wavelengths. Or, with the aid of nonlinear optics, Nd:YAG lasers can produce wavelengths in the visible, such as the green line of laser pointers, and even in the ultraviolet. Diode lasers produce beams throughout the infrared spectrum and in the short- and long-wavelength regions of the visible spectrum.

The yttrium–aluminum–garnet (YAG) and glass lasers listed are solid-state lasers. The light is generated in a solid, crystalline rod that looks much like a cocktail swizzlestick. The ytterbium-doped fiber laser is also a solid-state laser, but the solid is a thin glass fiber. Diode lasers are also solid-state devices, but through the fickleness of human terminology, the term "solid-state laser" is usually understood to include lasers such as Nd:YAG and glass, but not diode lasers. Diode lasers are based on semiconductors, and in many ways resemble high-powered light-emitting diodes.

All the other lasers listed are gas lasers that generate light in a gaseous medium, in some ways like a neon sign. If there are solid-state lasers and gaseous lasers, it is logical to ask if there is such a thing as a liquid laser. The answer is yes. The most common example is the organic dye laser, in which dye dissolved in a liquid produces the laser light.

1.1 WHAT ARE LASERS USED FOR?

We have seen that lasers usually do not produce a lot of power. By comparison, an ordinary 1200 W electric hair dryer is more powerful than 99% of the lasers in the world today. And we have seen that some types of lasers do not even produce power very efficiently, often wasting at least 99% of the electricity they consume.* So

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*An important exception is the diode laser, whose efficiency can sometimes be 70%.

what is all the excitement about? What makes lasers so special, and what are they really used for?

The unique characteristics of laser light are what make lasers so special. The capability to produce a narrow beam does not sound very exciting, but it is the critical factor in most laser applications. Because a laser beam is so narrow, it can read the minute, encoded information on a CD or DVD, or on the bar-code patterns in a grocery store. Because a laser beam is so narrow, the comparatively modest power of a 200 W carbon-dioxide laser can be focused to an intensity that can cut or weld metal. Because a laser beam is so narrow, it can create tiny and wonderfully precise patterns in a laser printer.

The other characteristics of laser light—its spectral purity and the way its waves are aligned—are also important for some applications. And, strictly speaking, the narrow beam could not exist if the light did not also have the other two characteristics. But from a simple-minded, applications-oriented viewpoint, a laser can often be thought of as nothing more than a flashlight that produces a very narrow beam of light.

One of the leading laser applications is materials processing, in which lasers cut, drill, weld, heat-treat, and otherwise alter both metals and nonmetals. Lasers can drill tiny holes in turbine blades more quickly and less expensively than mechanical drills. Lasers have several advantages over conventional techniques of cutting materials. For one thing, unlike saw blades or knife blades, lasers never get dull. For another, lasers make cuts with better edge quality than most mechanical cutters. The edges of metal parts cut by lasers rarely need be filed or polished because the laser makes such a clean cut.

Laser welding can often be more precise and less expensive than conventional welding. Moreover, laser welding is more compatible with robotics, and several large machine-tool builders offer fully automated laser-welding systems to manufacturers.

Laser heat-treating involves heating a metal part with laser light, increasing its temperature to the point where its crystal structure changes. It is often possible to harden the surface in this manner, making it more resistant to wear. Heat-treating requires some of the most powerful industrial lasers, and it is one application in which the raw power of the laser is probably more important than the narrow beam.

Have you purchased a quart of milk or anything else with a "Use by" date on it recently? Odds are, that date was put there with a laser. Laser marking is the largest market for materials-processing lasers, in terms of the number of lasers sold.

1.2 LASERS IN TELECOMMUNICATIONS

One of the more exciting applications of lasers is in the field of telecommunications, in which tiny diode lasers generate the optical signal transmitted through optical fibers. Because the bandwidth of these fiber-optic systems is so much greater than that of conventional copper wires, fiber optics is playing a major role in enabling the fast-growing Internet.

Many modern fiber-optic telecommunication systems transmit multiple wavelengths through a single fiber, a technique called wavelength-division multiplexing.

The evolution of this technology, together with erbium-doped fiber amplifiers to boost the signal at strategic points along the transmission line, is a major driving force in today's optoelectronics market.

Any time you pick up a telephone or connect to the Internet, it is likely that, somewhere along the line, you are transmitting information across a fiber-optic link. But today, optical technology is starting to transmit data over much smaller distances, even from one point to another inside your computer. As electronic devices—computers, phones, and readers—get smaller and smaller, eventually they run into a roadblock. Because electrons push each other around (repel each other, actually), there is a limit on how close together they can be. One beam of light, however, exerts no force on another beam. Hence, transmitting information with light instead of electrons avoids the roadblock to further miniaturization.

1.3 LASERS IN RESEARCH AND MEDICINE

Lasers started out in research laboratories, and many of the most sophisticated ones are still being used there. Chemists, biologists, spectroscopists, and other scientists count lasers among the most powerful investigational tools of modern science. Again, the laser's narrow beam is valuable, but in the laboratory the other characteristics of laser light are often important too. Because a laser's beam contains light of such pure color, it can probe the dynamics of a chemical reaction while it happens or it can even stimulate a reaction to happen.

In medicine, the laser's narrow beam has proven a powerful tool for therapy. In particular, the carbon dioxide laser has been widely adopted by surgeons as a bloodless scalpel because the beam cauterizes an incision even as it is made. Indeed, some surgeries that cause profuse bleeding had been impossible to perform before the advent of the laser. The laser is especially useful in ophthalmic surgery because the beam can pass through the pupil of the eye and weld, cut, or cauterize tissue inside the eye. Before lasers, any procedure inside the eye necessitated cutting open the eyeball. The LASIK procedure, described in Chapter 18, can correct vision so people no longer need glasses or contract lenses. Lasers also are used for gum surgery, to selectively destroy cancer cells, and even to treat toenail fungus.

1.4 LASERS IN GRAPHICS AND GROCERY STORES

Laser printers are capable of producing high-quality output at very high speeds. Twenty-five years ago, they were also very expensive, but good, PC-compatible laser printers can now be obtained for less than a hundred dollars. In a laser printer, the laser "writes" on an electrostatic surface, which, in turn, transfers toner (ink) to the paper.

Lasers have other applications in graphics as well. Laser typesetters write directly on light-sensitive paper, producing camera-ready copy for the publishing industry. Laser color separators analyze a color photograph and create the information a printer needs to print the photograph with four colors of ink. Laser platemakers produce the printing plates, or negatives in some cases, so that national newspapers such as the *Wall Street Journal* and *USA Today* can be printed in locations far from their editorial offices.

And everyone has seen the laser bar-code scanners at the checkout stand of the local grocery store. The narrow beam of the laser in these machines scans the bar-code pattern, automatically reading it into the store's computer.

1.5 LASERS IN THE MILITARY

So far, lasers have been found to make poor weapons, and many scientists believe that engineering complexities and the laws of physics may prevent them from ever being particularly useful for this purpose. Nonetheless, many thousands of lasers have found military applications, not in weapons, but in range finders and target designators.

A laser range finder measures the time a pulse of light takes to travel from the range finder to the target and back. An on-board computer divides this number into the speed of light to find the range to the target. A target designator illuminates the target with infrared laser light, and then a piece of "smart" ordnance, a rocket or bomb, equipped with an infrared sensor and some steering mechanism, homes in on the target and destroys it.

Diode lasers are sometimes used to assist in aiming small arms. The laser beam is prealigned along the trajectory of the bullet, and a policeman or soldier can see where the bullet will hit before firing.

Diode lasers are used as military training devices in a scheme that has been mimicked by civilian toy manufacturers. Trainees use rifles that fire bursts of diode-laser light (rather than bullets) and wear an array of optical detectors that score a hit when an opponent fires at them.

1.6 OTHER LASER APPLICATIONS

There seems to be no end to the ingenious ways a narrow beam of light can be put to use. In sawmills, lasers are used to align logs relative to the saw. The laser projects a visible stripe on the log to show where the saw will cut it as the sawman moves the log into the correct position. On construction projects, the narrow beam from a laser guides heavy earth-moving equipment. Laser light-shows herald the introduction of new automobile models and rock concerts. And laser gyroscopes guide many commercial aircraft (an application that depends more on a laser's spectral purity than on its narrow beam).

Chapter 2

The Nature of Light

What is light? How does it get from one place to another? These are the questions that are addressed in this chapter. But the answers are not all that easy. The nature of light is a difficult concept to grasp because light does not always act the same way. Sometimes it behaves as if it were composed of tiny waves, and other times it behaves as if it were composed of tiny particles. Let us take a look at how light waves act and at how light particles (photons) act, and then we will discuss this so-called "duality" of light.

2.1 ELECTROMAGNETIC WAVES

"Light is a transverse electromagnetic wave" is a simple sentence. But what does that mean? Let us take the phrase "transverse electromagnetic wave" apart and examine it one word at a time.

Figure 2.1 is a schematic of a wave. It is a periodic undulation of something—maybe the surface of a pond, if it is a water wave—that moves with characteristic velocity, v. The wavelength, λ, is the length of one period, as shown in Figure 2.1. The frequency of the wave is equal to the number of wavelengths that move past an observer in one second. It follows that the faster the wave moves—or the shorter its wavelength—the higher its frequency will be. Mathematically, the expression

$$f = v/\lambda$$

relates the velocity of any wave to its frequency f and wavelength λ.

The amplitude of the wave in Figure 2.1 is its height, the distance from the center line to the peak of the wave. The phase of the wave refers to the particular part of the wave passing the observer. As shown in Figure 2.1, the wave's phase is 90° when it is at its peak, 270° at the bottom of a valley, and so on.

So much for waves. What does transverse mean? There are two kinds of waves: transverse and longitudinal. In a transverse wave, whatever is waving is doing so in a direction transverse (perpendicular) to the direction in which the wave is moving. A water wave is an example of a transverse wave because the thing that is waving (the surface of the water) is moving up and down, while the wave itself is moving horizontally across the surface. Ordinary sound, on the other hand, is an example of a longitudinal wave. When a sound wave propagates through air, the compressions

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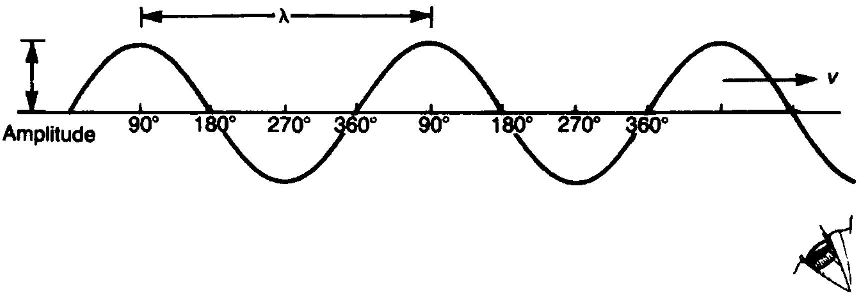

Figure 2.1 A wave and an observer.

and rarefactions are caused by gas molecules moving back and forth in the same direction that the wave is moving. Light is a transverse wave because the things that are waving—electric and magnetic fields—are doing so in a direction transverse to the direction of wave propagation.

Light is an electromagnetic wave because the things that are waving are electric and magnetic fields. Figure 2.2 is a diagram of the fields of a light wave. It has an electric field (*E*) undulating in the vertical direction and a magnetic field (*B*) undulating in the horizontal direction.* The wave can propagate through a vacuum because, unlike sound waves or water waves, it does not need a medium to support it. If the light wave is propagating in a vacuum, it moves at a velocity $c = 3.0 \times 10^8$ m/s, the speed of light.†

Visible light is only a small portion of the electromagnetic spectrum diagrammed in Figure 2.3. Radio waves, light waves, and gamma rays are all transverse electromagnetic waves, differing only in their wavelength. But what a difference that is! Electromagnetic waves range from radio waves hundreds or thousands of meters long down to gamma rays, whose tiny wavelengths are on the order of 10^{-12} m. And the behavior of the waves in different portions of the electromagnetic spectrum varies radically, too.

But we are going to confine our attention to the "optical" portion of the spectrum, which usually means part of the infrared, the visible portion, and part of the ultraviolet. Specifically, laser technology is usually concerned with wavelengths between about 10 μm (10^{-5} m) and 100 nm (10^{-7} m). The visible portion of the spectrum, roughly between 400 and 700 nm, is shown across the bottom of Figure 2.3.

The classical (i.e., nonquantum) behavior of light—and all other electromagnetic radiation—is completely described by an elegant set of four equations called Maxwell's equations, named after the nineteenth century Scottish physicist James Clerk Maxwell. Maxwell collected the conclusions of several other physicists and then modified and combined them to produce a unified theory of electromagnetic

---

*Although it would make sense to use *M* to designate a magnetic field, that is not the letter physicists have chosen. *B* is the accepted letter to designate a magnetic field.

†It is convenient to remember that the speed of light is about 1 ft/ns. Thus, when a laser produces a 3 ns pulse, the pulse is about 3 ft long.

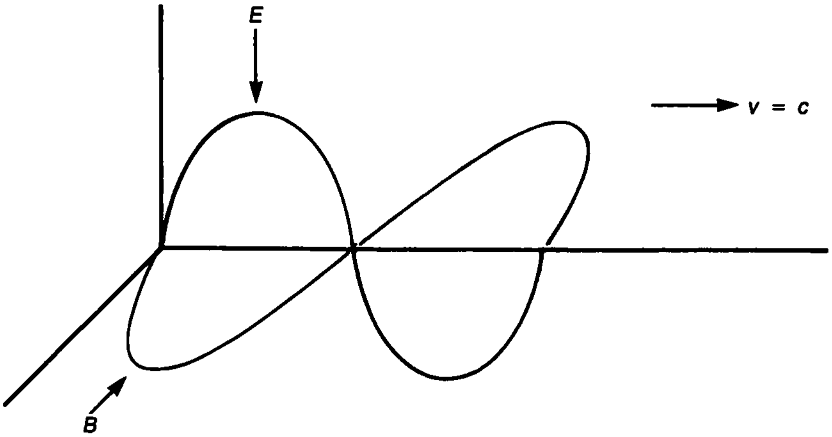

Figure 2.2 The electric (E) and magnetic (B) fields of a light wave.

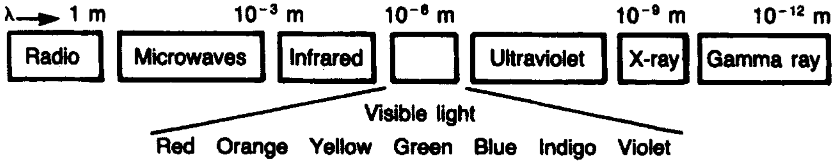

Figure 2.3 The electromagnetic spectrum.

phenomena. His equations are among the most important in physics. Here is what they look like in a vacuum:

$$\nabla \times E = 0$$

$$\nabla \times B = 0$$

$$\nabla \times E + \frac{\partial B}{\partial t} = 0$$

$$\nabla \times B = c^{-2} \frac{\partial E}{\partial t}$$

where c is the speed of light.

Now, these are differential equations, but you do not have to understand differential calculus to appreciate their simplicity and beauty.* The first one—Gauss's law

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*$\nabla \times E$ is read "divergence of E"; $\nabla \times E$ is read "curl of E"; and $\partial E/\partial t$ is read "partial time derivative of E."

for electricity—describes the shape of an electric field (E) created by electric charge (ρ). The second equation—Gauss's law for magnetism—describes the shape of a magnetic field (B) created by a magnet. The fact that the right side of this equation is zero means that it is impossible to have a magnetic monopole (e.g., a north pole without a south pole).

An electric field is created by electric charge, as described by Gauss's law, but an electric field is also created by a time-varying magnetic field, as described by Faraday's law (the third equation). Likewise, a magnetic field can be created by a time-varying electric field and also by an electric current, J.* The shape of this magnetic field is described by Ampere's law, the fourth equation.

The fame of these four little equations is well justified, for they govern all classical electrodynamics and their validity even extends into the realm of quantum and relativistic phenomena. We will not be dealing directly with Maxwell's equations any more in this book, but they have been included in our discussion to give you a glimpse at the elegance and simplicity of the basic laws that govern all classical electromagnetic phenomena.

There are two special shapes of light waves that merit description here. Both of these waves have distinctive wavefronts. A *wavefront* is a surface of constant phase. An example is the plane wave in Figure 2.4. The surface sketched passes through the wave at its maximum. Because this surface that cuts through the wave at constant phase is a plane, the wave is a *plane wave.*

The second special shape is a spherical wave, and, as you might guess, it is a wave whose wavefronts are spheres. A cross-sectional slice through a spherical wave in Figure 2.5 shows several wavefronts. A spherical wavefront is the three-dimensional analogy of the two-dimensional "ripple" wavefront produced when you drop a pebble into a pond. A spherical wave is similarly produced by a point source, but it spreads in all three dimensions.

2.2 WAVE-PARTICLE DUALITY

Let us do a thought experiment with water waves. Imagine a shallow pan of water 3 ft wide and 7 ft long. Figure 2.6 shows the waves that spread out in the pan if you strike the surface of the water rapidly at point A. Now look at what happens at points X and Y. A wave crest will arrive at Y first because Y is closer to the source (Point A) than X is. In fact, if you pick the size of the pan correctly, you can arrange for a crest to reach X just as a trough arrives at Y, and vice versa.

On the other hand, if you strike the water at point B, the wave crest will arrive at X first. But (assuming you are still using the correct-size pan) there will still always be a crest arriving at X just as a trough arrives at Y, and vice versa.

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*Because there are not enough letters in the English (and Greek) alphabets to go around, some letters must serve double duty. For example, in Maxwell's equations E represents the electric-field vector, but elsewhere in this book it stands for energy. In Maxwell's equations, J represents an electric-current density and B represents the magnetic-field vector, but elsewhere J is used as an abbreviation for joules and B for brightness. The letter f is used to mean frequency and to designate the focal length of a lens. The letters and abbreviations used in this book are consistent with most current technical literature.

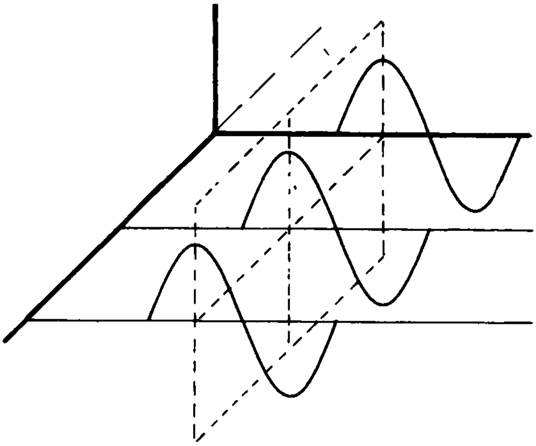

Figure 2.4 A plane wave.

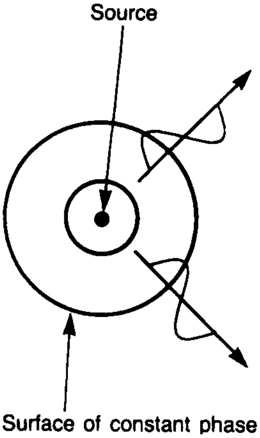

Figure 2.5 A spherical wave.

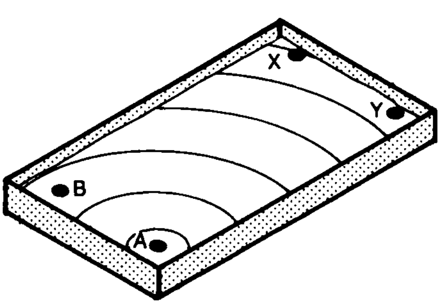

Figure 2.6 Wave experiment in a shallow pan of water.

What happens if you strike the water at A and B simultaneously? At point X, a crest from A will arrive at exactly the same time as a trough arrives from B. Likewise, a crest from B will be canceled out by a trough from A. At point X, the surface of the water will be motionless. The same argument holds for point Y. But at a point halfway between X and Y, where crests from A and B arrive simultaneously, there will be twice as much motion as there was before.

This is the phenomenon of interference: waves interacting with each other to cancel or enhance each other.

A similar situation can be observed with light, as diagrammed in Figure 2.7. Here, two slits correspond to the sources, and dark stripes on a viewing screen correspond to motionless water at points X and Y. This arrangement, called Young's double-slit experiment, is analyzed in detail in Chapter 5. But here is the point for now: the only way to explain the observed results is to postulate that light is behaving as a wave. There is no possible way to explain the bright spot at the center of the screen if you assume that the light is made up of particles. However, it is easily explained if you assume light is a wave.

During most of the nineteenth century, physicists devised experiments like this one and explained their results quite successfully from the assumption that light is a wave. But near the turn of the century, a problem developed in explaining the photoelectric effect.

A photoelectric cell, shown schematically in Figure 2.8, consists of two electrodes in an evacuated tube. When light strikes the cathode, the energy in the light can liberate electrons from the cathode, and these electrons can be collected at the anode. The resulting current is measured with an ammeter (A). It is a simple experiment to measure the current collected as a function of the voltage applied to the electrodes, and the data look like the plot in Figure 2.9.

There is a lot of information in Figure 2.9. The fact that current does not change with positive voltage (voltage that accelerates the electrons toward the anode) im-

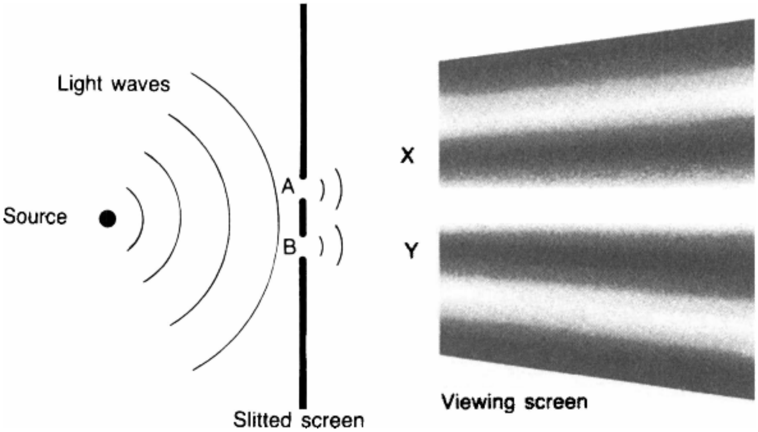

Figure 2.7 Optical analogy to wave experiment in Figure 2.6.

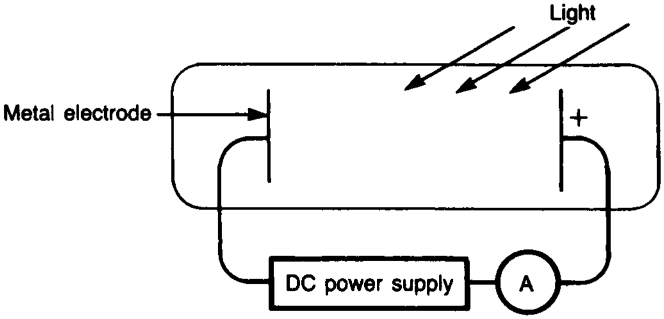

Figure 2.8 A photoelectric cell.

plies that every electron emitted from the cathode has at least some kinetic energy. In other words, an electron emitted from the cathode does not need any help to get to the anode. But as soon as the voltage starts to go negative, the current decreases. This implies that some of the electrons are emitted with very little energy; if they have to climb even a small voltage hill, they do not make it to the anode. The sharp cutoff of current implies that there is a definite maximum energy with which electrons are emitted from the cathode.

Thus, some electrons are emitted with high energy, and some barely get out of the cathode. This makes sense if you assume that the high-energy electrons came from near the surface of the cathode whereas the low-energy ones had to work their way out from farther inside the cathode. What is hard to understand is why the maximum energy for emitted electrons does not depend on the intensity of the light illuminating the cathode.

Think about it for a moment. The electric field in the light wave is supposed to be exerting a force on the electrons in the cathode. The field vibrates the electrons,

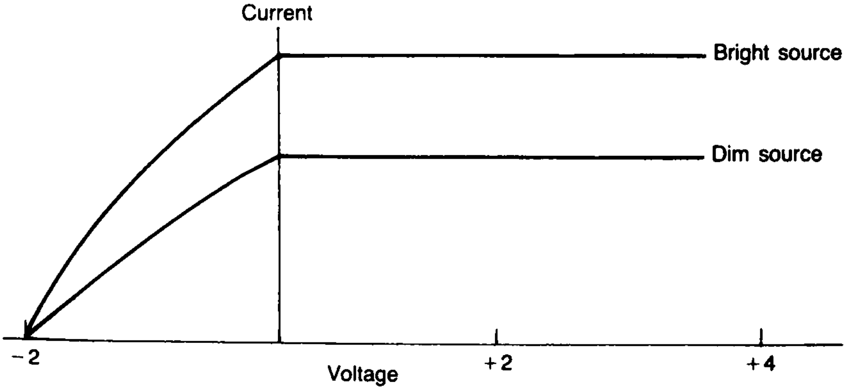

Figure 2.9 Current versus voltage for a photoelectric cell.

shaking them so they can break free from the cathode. As the illumination intensifies—that is, the electric-field strength increases—the energy of vibration should increase. An electron right on the surface of the cathode should break free with more energy than it did before the illumination intensity was increased. That is, the current from the bright source in Figure 2.9 should go to zero at a greater negative voltage than it does from the dim source. But that is not what happens.

There are other problems. For example, you can easily figure out how much energy the most energetic electrons have when they leave the cathode. (For the experiment whose data appear in Figure 2.9, those electrons would have 2 eV of energy.) If all the energy falling on an atom can somehow be absorbed by one electron, how long does it take that electron to accumulate 2 eV of energy?

The rate at which energy hits the whole surface is known from the illumination intensity. To calculate the rate at which energy hits a single atom, you have to know how big the atom is. Both now and back at the turn of the nineteenth century, when all this confusion was taking place, scientists knew that an atomic diameter was on the order of 10^{-8} cm. For typical illumination intensities of a fraction of a microwatt per square centimeter, it takes a minute or two for an atom to absorb 2 eV. But in the laboratory, the electrons appear immediately after the light is turned on with a delay of much less than a microsecond. How can they absorb energy that quickly?

In 1905, Albert Einstein proposed a solution to the dilemma. He suggested that light is composed of tiny particles called photons, each photon having energy

$$E = hf$$

in which f is the frequency of the light, and h is Planck's constant ($h = 6.63 \times 10^{-34}$J-s). This takes care of the problem of instantaneous electrons. If light hits the cathode in discrete particles, one atom can absorb one photon while several million of its neighbors absorb no energy. Thus, the electron from the atom that was hit can be liberated immediately.

Einstein's theory also explains why the maximum energy of electrons emitted from the cathode does not depend on illumination intensity. If each liberated electron has absorbed the energy of one photon, then the most energetic electrons (those that came right from on the surface of the cathode) will have energy almost equal to the photon energy. But increasing the illumination intensity means more photons, not more energy per photon. So a brighter source will result in more electrons but not more energy per electron. That is exactly the result shown in Figure 2.9.

On the other hand, changing the color of light—that is, changing its wavelength and, therefore, its frequency—will change the energy per photon. In subsequent experiments, other physicists changed the color of light hitting the cathode of a photocell and observed data like those shown in Figure 2.10. As the energy of the incident photons increases, so does the maximum energy of the photoelectrons.

Thus, Einstein's photons explained not only the photoelectric effect but also other experiments that were conducted later that defied explanation from the wave theory. But what about experiments like Young's double-slit experiment, which absolutely cannot be explained unless light behaves as a wave? How was it possible to resolve the seemingly hopeless contradiction?

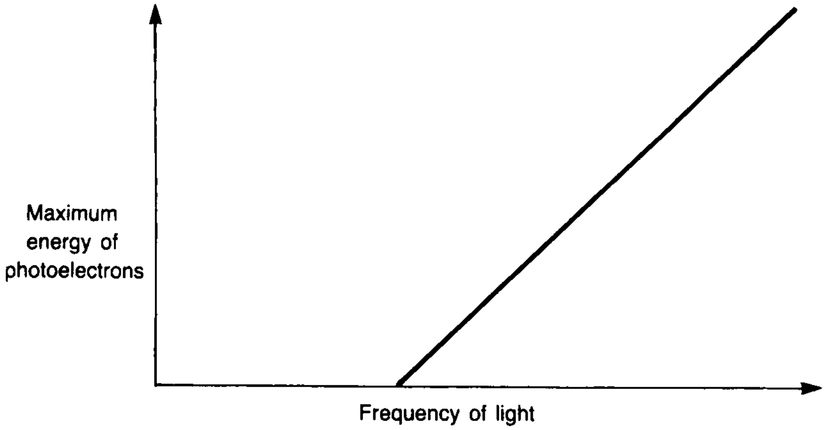

Figure 2.10 Energy of liberated electrons increases with photon energy.

The science of quantum mechanics developed during the early years of the twentieth century to explain this and other contradictions in classical physics. Quantum mechanics predicts that when nature is operating on a very tiny scale (an atomic scale or smaller), it behaves much differently than it does on a normal, "people-sized" scale, so intuition has to be reeducated to be reliable on an atomic scale.

As a result of quantum mechanics, physicists now believe that the dual nature of light is not a contradiction. In fact, quantum mechanics predicts that particles also have a wavelike property, and experiments have proven that this property exists. By reeducating their intuitions to deal reliably with events on an atomic scale, physicists have found that the duality of light is not a contradiction of nature but a manifestation of nature's extraordinary complexity.

If a laser produces a 1 ns, 1 J pulse of light whose wavelength is 1.06 μm, there are two ways you can think of that light. As shown in Figure 2.11, you can think of that pulse as a foot-long undulating electric and magnetic field. The period of the undulation is 1.06 μm, and the wave moves to the right at the speed of light. On the other hand, you could think of the laser pulse as a collection of photons, as shown in Figure 2.12. All the photons are moving to the right at the speed of light, and each photon has energy $E = hf = hc/\lambda$.

Either way of thinking of the pulse is correct, provided that you realize neither way tells you exactly what the pulse is. Light is neither a wave nor a particle, but it

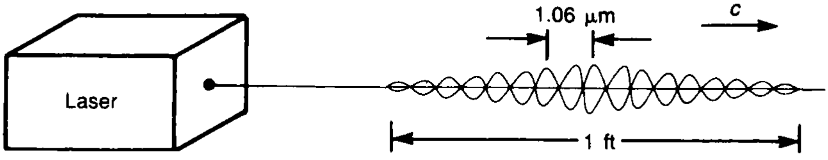

Figure 2.11 A 1 J, 1 ns pulse of 1.06 μm laser light pictured as a wave.

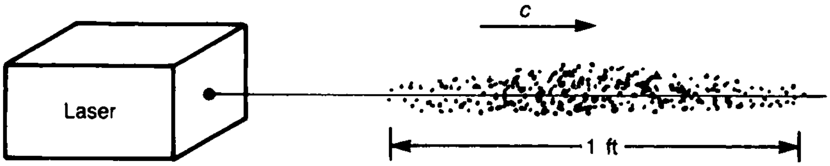

Figure 2.12 A 1 J, 1 ns pulse of 1.06 μm laser light pictured as photons.

is often convenient to think of light as one or the other in a particular situation. Sometimes, light can act as both a wave and a particle simultaneously. For example, you could envision illuminating the cathode of a photocell with stripes of light from Young's experiment. Electrons would still be liberated instantaneously in the photocell, proving the particle-like nature of light despite the stripes, which prove light's wavelike nature.

QUESTIONS

1. What is the frequency of green light whose wavelength is $\lambda = 530$ nm? Roughly how many nanoseconds does it take this light to travel from one end of a 100-yd-long football field to the other?
2. Sketch Figure 2.3 on a piece of paper. Beneath the figure, add the frequencies of the electromagnetic radiation that correspond to the wavelengths given above the figure.
3. A compass will not work properly underneath a high-voltage power line. Which of Maxwell's equations accounts for this? Which of Maxwell's equations describes the earth's magnetic field?
4. Calculate the frequency of the light wave emerging from the laser in Figure 2.11. Calculate the number of photons emerging from the laser in Figure 2.12.