Jeff Hecht

Understanding Lasers

FOURTH EDITION

An Entry-Level Guide

IEEE PRESS

WILEY

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IEEE Press
445 Hoes Lane
Piscataway, NJ 08854

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Published by John Wiley & Sons, Inc., Hoboken, New Jersey.
Published simultaneously in Canada.

Library of Congress Cataloging-in-Publication Data is available.

hardback: 9781119310648

Cover Design: Wiley
Cover Image: tiero/ Getty Images

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1

To my many friends in the optics community, to the many people who have given graciously of their time helping me understand more about optics, people, and the world around us, and to the coming generation in hope this book helps you get started in the fascinating world of lasers and optics.

CONTENTS

PREFACE

"For Credible Lasers, See Inside."

THE LASER IS LESS THAN three years younger than the space age. Just days after the Soviet Union launched Sputnik I on October 4, 1957, Charles Townes and Gordon Gould had two crucial discussions at Columbia University about the idea that would become the laser. As the United States and Soviets launched the space race, Townes and Gould went their separate ways and started their own race to make the laser. On May 16, 1960, Theodore Maiman crossed the laser finish line, demonstrating the world's first laser at Hughes Research Laboratories in California.

Bright, coherent, and tightly focused, laser beams were a new kind of light that excited the imagination. Science fiction writers turned their fictional ray guns into lasers with a stroke of the pen. Science writers inhaled deeply of the technological optimism of the early 1960s and wrote breathless predictions about the future of "the incredible laser." An article in the November 11, 1962, issue of the Sunday newspaper supplement *This Week* revealed U.S. Army schemes for equipping soldiers with a "death-ray gun … small enough to be carried or worn as a side-arm." It quoted Air Force Chief of Staff Curtis E. LeMay predicting that ground-based lasers could zap incoming missiles at the speed of light.

The reality was something else. A bemused Arthur Schawlow, who had worked with Townes on the laser, posted a copy of "The Incredible Laser" on his door at Stanford University, along with a note that read, "For credible lasers, see inside." Irnee D'Haenens, who had helped Maiman make the first laser, called the laser "a solution looking for a problem," a joke that summed up the real situation and became a catchphrase for the young laser industry. The infant laser had tremendous potential, but it had to grow up first.

D'Haenens's joke lasted many years. So did the popular misconception that lasers were science-fictional weapons. If you told your neighbors you worked with lasers in the 1970s, they inevitably thought you were building death rays. That began to change as supermarkets installed laser scanners to automate checkout in the early 1980s. Then lasers began playing music on compact disks. Laser printers, laser pointers, CD-ROMs, and DVD players followed. Laser surgery became common, particularly to treat eye disease. Surveyors, farmers, and construction workers used lasers to draw straight lines in their work. Lasers marked serial numbers on products, drilled holes in baby-bottle nipples, and performed a thousand obscure tasks in the industry. Lasers transmitted billions of bits per second through optical fibers, becoming the backbone of the global telecommunications network and the internet.

The incredible laser has become credible, a global business with annual sales in the billions of dollars. Lasers have spread throughout science, medicine, and industry. Laser-generated digital signals are the heavy traffic on the fiber-optic backbone of the global information network. Lasers are essential components in home electronics, buried inside today's CD, DVD, and Blu-Ray players. Laser pointers are so cheap that they are cat toys. It is a rare household that does not own at least one laser, though most are hidden inside electronics or other things. Yet, lasers have not become merely routine; they still play vital roles in Nobel-grade scientific research.

This book will tell you about these real-world lasers. To borrow Schawlow's line, "For credible lasers, see inside." It will tell you how lasers work, what they do, and how they are used. It is arranged somewhat like a textbook, but you can read it on your own to learn about the field. Each chapter starts by stating what it will cover, ends by reviewing key points, and is followed by a short multiple-choice quiz.

We start with a broad overview of lasers. Chapter 2 reviews key concepts of physics and optics that are essential to understand lasers. You should review this even if you have a background in physics, especially to check basic optical concepts and terms. Chapters 3 and 4 describe what makes a laser work and how lasers operate. Chapter 5 describes the optical accessories used with lasers. Try to master each of these chapters before going on to the next.

Chapters 6 to 11 describe various types of lasers. Chapter 6 gives an overview of laser types and configurations and explains such critical concepts as the difference between laser oscillation and amplification, the importance of laser gain, and tunable lasers. Chapter 7 describes the workings of gas lasers and important types such as the helium-neon and carbon dioxide lasers. Chapter 8 covers solid-state lasers, from tiny green laser pointers to giant laboratory systems. Chapter 9 covers fiber lasers, the fastest-growing solid-state laser, now widely used in the industry because of its power and high efficiency, along with fiber amplifiers used in telecommunications. Chapter 10 covers the hot area of semiconductor diode lasers, ranging from tiny chips to powerful pumps for other lasers. Chapter 11 describes other types of lasers, including tunable dye lasers, extreme ultraviolet sources, and free-electron lasers.

The final three chapters cover laser applications, divided into three groups. Chapter 12 describes low-power applications, including communications, measurement, and optical data storage. Chapter 13 covers high-power applications, including surgery, industrial materials processing, and laser weapons. Chapter 14 focuses on research and emerging developments in areas including spectroscopy, slow light, laser cooling, and extremely precise measurements. The appendices, glossary, and index are included to help make this book a useful reference.

To keep this book to a reasonable length, we concentrate on lasers and their workings. We cover optics and laser applications only in brief, but after reading this book, you may want to study them in more detail.

I met my first laser in college and have been writing about laser technology since 1974. I have found it fascinating, and I hope you will, too.

JEFF HECHT

Auburndale, Massachusetts

CHAPTER 1

INTRODUCTION AND OVERVIEW

ABOUT THIS CHAPTER

This chapter will introduce you to lasers. It will give you a basic idea of their use, their operation, and their important properties. This basic understanding will serve as a foundation for the more detailed descriptions of lasers and their operation in later chapters. After a brief introduction to lasers, this chapter will introduce important laser properties and applications.

1.1 LASERS, OPTICS, AND PHOTONICS

To understand lasers, you should first understand where lasers fit into the broader science and technology of light. That field was long called *optics*, but now part of it is sometimes called *photonics*. The differences in the meanings of the two words reflect how the field has changed since the mid-20th century, and understanding those differences will help you understand both lasers and the larger world of light, optics and photonics.

Optics dates back to the origin of lenses in ancient times. It is the science of telescopes, spectacles, microscopes, binoculars, and other optical instruments that manipulate light using lenses, mirrors, prisms, and other transparent and reflective objects. Isaac

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Newton famously described the fundamentals of optics in his 1704 book *Opticks*. He thought light was made of tiny particles, but a century later an experiment by Thomas Young indicated light was made of waves, and opinion shifted for a while.

In the late 19th century, physicists discovered that light was a type of electromagnetic radiation, along with radio, infrared, ultraviolet, X-rays, and gamma rays. They differ in the lengths of the waves and in how fast they oscillate. The wavelength and frequency depend on each other because electromagnetic waves always travel at the speed of light. In the early 20th century, Albert Einstein showed that electromagnetic radiation could behave both as particles—called *photons*—and as waves, depending on how you looked at them. The only fundamental difference among electromagnetic waves was their wavelength, which could also be measured as frequency or (photon) energy.

The science and technology of light have also grown increasingly connected with electronics in the past century. Electronic devices can measure light by converting it into electronic signals and measuring them. Television cameras and displays include both optics and electronics. The first electronic circuits used vacuum tubes, but semiconductor devices began replacing tubes in the mid-20th century. That brought a new generation of *electro-optic* devices, including semiconductor electronics that emitted and detected light, converting signals and energy back and forth between photons and electrons.

In the late 20th century, the word *photonics* was coined to describe devices that manipulate photons, like electronics manipulate electrons. The use of the new term became controversial because many people who worked in optics in the field saw it as an attempt to "rebrand" their profession. Photonics has come to refer to things that manipulate light when it acts more like a particle (a photon) than a wave. By that definition, a laser or a sensor that converts light (a series of photons) into an electronic signal is considered photonics, but a lens that refracts and focuses light waves is considered optics. However, that definition remains somewhat hazy. Today, both terms are used, but at this writing, Google tells us that optics remains far ahead, indexed on 622 million web pages, compared to a mere 17.6 million for photonics.

Whatever you want to call the field, you should learn the physical basics of light, optics and photonics, to understand how lasers work. Chapter 2 will go into more detail.

1.2 UNDERSTANDING THE LASER

The laser was born in 1960, long before the word “photonics” came into use. Lasers retain a youthful image, thanks largely to continuing advances in the technology. They vary widely. Some lasers are tremendously sophisticated and incredibly precise scientific instruments costing tens or hundreds of thousands of dollars. Others are tiny semiconductor chips hidden inside optical disk players or pen-shaped red pointers used as cat toys. The world’s biggest laser, the National Ignition Facility at the Lawrence Livermore National Laboratory, cost over a billion dollars and fills an entire building. The tiny lasers inside CD or DVD players are the size of grains of sand and cost pennies apiece. Red laser pointers sell for only a few dollars and are often given away.

We now take many laser applications for granted. For decades, laser scanners at store checkouts have read bar codes printed on packages to tally prices and manage their inventory. Laser pulses carried through optical fibers are the backbone of the global telecommunications network. Builders use laser beams to make sure walls and ceilings are flat and smooth. Offices use laser printers to produce documents. Medical and scientific instruments use lasers to make precise measurements. Lasers cut sheets of metals, plastics, and other materials to desired shapes, so some parts of your car are likely made with a laser. Chapters 12–14 describe many more examples.

Laser light has special properties that make it useful in many ways. You can think of a laser as a very well-behaved light bulb, emitting a narrow beam of a single color rather than spreading white light all around a room. You would not use a laser to illuminate a room, but you can use a tightly focused single-color laser beam to make precise measurements, to transport information around the world at the speed of light, or to cut sheets of metal. Lasers have become tools in industry, medicine, engineering, and science, as well as components in optical systems.

Lasers come in many forms. The most common lasers are tiny semiconductor chips that look like tiny pieces of metallic confetti; untold millions of them are hidden inside electronic devices, measuring devices, and communication systems. Others are glassy or crystalline solids in the form of rods, slabs, or fibers. Some are tubes filled with gases that emit laser light. Some emit light so feeble that the eye can barely detect it; others are blindingly bright; and many emit infrared or ultraviolet light outside the human visible spectrum. Some perform delicate surgery; others weld sheets of metal. Lasers are used by construction workers installing ceilings and by scientists detecting gravitational waves.

What makes them all lasers is that they generate light in the same way, by a process called "light amplification by the stimulated emission of radiation" that gave us the word "LASER." We will start by explaining what makes laser light differ from that from the sun, light bulbs, flames, and other light sources.

1.3 WHAT IS A LASER?

Each part of the phrase "light amplification by the stimulated emission of radiation" has a special meaning, so we will look at it piece by piece, starting from the final word.

Radiation means *electromagnetic radiation,* a massless form of energy that travels at the speed of light. It comes in various forms, including visible light, infrared, ultraviolet, radio waves, microwaves, and X-rays. Light and other forms of electromagnetic radiation behave like both waves and particles (called *photons*). You will learn more details in Chapter 2.

Stimulated emission tells us that lasers produce light in a special way. The sun, flames, and light bulbs all emit light *spontaneously*, on their own, in order to release extra internal energy. Lasers contain atoms or molecules that release their extra energy when other light *stimulates* them. You will learn more about that process, called stimulated emission, in Chapter 3.

Amplification means increasing the amount of light. In stimulated emission, an input light wave stimulates an atom or molecule to release its energy as a second wave, which is perfectly matched to the input wave. The stimulated wave, in turn, can stimulate other atoms or molecules to emit duplicate waves, amplifying the light signal more. It may be easier to think of stimulated emission as one light photon tickling or stimulating an atom or molecule so it releases an identical photon, which in turn can stimulate the emission of another identical photon, producing a cascade of photons that amplifies the light.

Light describes the type of electromagnetic radiation produced. In practice, that means not just light visible to the human eye, but also adjacent parts of the electromagnetic spectrum that our eyes cannot see because it is either longer in wavelength (infrared) or shorter in wavelength (ultraviolet.)

It took decades to put the pieces together. Albert Einstein suggested the possibility of stimulated emission in a paper published in 1917. Stimulated emission was first observed in the 1920s, but physicists long expected it to be much weaker than spontaneous emission. The first hints that stimulated emission could be stronger came in radio-frequency experiments shortly after World War II. In 1951, Charles H. Townes, then at Columbia University, thought of a way to stimulate the emission of microwaves. His idea was to direct ammonia molecules carrying extra energy into a cavity that would reflect the microwaves back and forth through the gas. He called his device a *maser*, an acronym for "microwave amplification by the stimulated emission of radiation."

It took until 1954 for Townes and his graduate student James Gordon to make the maser work. Some ammonia molecules spontaneously emitted microwaves at a frequency of 24 gigahertz, and that spontaneous emission could stimulate other excited ammonia molecules to emit at the same frequency, building up a signal that oscillated on its own. Alternatively, an external 24-GHz signal could stimulate emission at that frequency from ammonia molecules, to amplify the signal.

In principle, the maser process could be extended to other types of electromagnetic waves, and in 1957, Townes started looking into prospects for an optical version of the maser. Early in his research, he talked with Gordon Gould, a Columbia graduate student who was using light to energize material he was studying for his doctoral research, a then-new idea called *optical pumping*. Townes soon enlisted the help of his brother-in-law, Arthur Schawlow, to work on the optical maser project. Gould, who dreamed of becoming an inventor, quietly tackled the same idea. They essentially solved the same physics problem independently, by placing mirrors at each end of a cylinder so the laser light could oscillate between them. Gould set out to patent his ideas; Townes and Schawlow published their proposal in a scientific journal, *Physical Review Letters.* Their work launched a race to build a laser, which I chronicled in *Beam: The Race to Make the Laser* (Oxford University Press, 2005).

Townes shared in the 1964 Nobel Prize in physics for his pioneering work on "the maser/laser principle." After a long series of legal battles, Gould earned tens of millions of dollars from his patent claims. However, a third physicist won the race to make the

Figure 1-1. Theodore Maiman and Irnee J. D'Haenens with a replica of the world's first laser, which they made at Hughes Research Laboratories in 1960. (Reprinted from Hughes Research Laboratories, courtesy of AIP Neils Bohr Library.)

first laser. On May 16, 1960, Theodore Maiman used a photographic flashlamp to excite a fingertip-sized crystal of synthetic ruby to emit pulses of red light from the world's first laser at Hughes Research Laboratories in Malibu, California. Figure 1-1 shows Maiman and his assistant Irnee D'Haenens holding a replica of his elegant little device.

The ruby laser illustrates how a laser works. Energy from an external source, the lamp, was absorbed by chromium atoms in the ruby cylinder. A few chromium atoms spontaneously emitted photons of red light, which traveled through the ruby. Silver film coated on the ends of the cylinder reflected the red photons back into the ruby, where they stimulated other excited chromium atoms to emit identical photons in the same direction, amplifying the light. Those photons bounced back and forth between the end mirrors, oscillating (as explained in Box 1.1) within the cavity formed by the two mirrors, with some light emerging through a hole in one coating to form the laser beam. The light was all at the same wavelength, 694 nanometers (1 nm = 10^{-9} meter) at the red end of the visible spectrum. It was also coherent, with all the waves aligned with each other and marching along in step like soldiers on parade.

Maiman's laser emitted a pulse of laser light every time the flashlamp fired, and pulsed operation proved attractive for some uses. Other lasers generated a continuous beam, which was attractive for other purposes. New laser materials followed, including crystals and glasses containing various light-emitting elements, tubes filled with mixtures of light-emitting gases, and tiny chips of semiconductor compounds such as gallium arsenide or gallium nitride, which today are the world's most common lasers.

BOX 1.1 LASER OSCILLATION

Stimulated emission amplifies light in a laser, but the laser itself is called an oscillator because it generates a beam on its own rather than amplifying light from an outside source. So you may wonder why the word "laser" comes from "light *amplification* by the stimulated emission of radiation"? There's an interesting bit of history behind that.

Charles Townes created the word "maser" as an acronym for microwave amplification by the stimulated emission of radiation. When he began thinking of a version of the maser that used light, he called it an optical maser. When Gordon Gould sat down to tackle the same problem, he wrote "laser" at the top of his notes, coining the acronym for light amplification by the stimulated emission of radiation. As the competition between Townes and Gould became intense, each side pushed its own term.

Arthur Schawlow was a jovial soul, and at one conference pointed out that because the laser was actually an oscillator, it should be described as "light oscillation by the stimulated emission of radiation," making the laser a "loser." Everybody laughed, but the word laser proved to be a winner.

Lasers operate at wavelengths from the far infrared all the way to X-rays. They can generate modest powers far below one watt, steady powers of thousands of watts, or concentrate light into pulses lasting less than a trillionth of a second. Chapters 2 through 5 will describe the basics of laser physics in more detail. Chapters 6 through 11 will describe various types of lasers, and Chapters 12 through 14 will explain important and important uses of lasers. But first let's take a quick look at various types of lasers and their properties.

1.4 LASER MATERIALS AND TYPES

Laser performance depends strongly on the materials from which they are made. Maiman won the laser race because he knew the optical properties of ruby and designed his laser to take advantage of them.

The ruby laser worked because Maiman used a flash lamp to produce a bright pulse of visible light that excited chromium atoms in the ruby rod to a higher energy level. The chromium atoms remained in that high energy level until they released their energy as red light and dropped to a lower energy level. Some of those photons then stimulated emission from other chromium atom, which also emitted red light, producing a cascade of red light that became a laser pulse. Figure 1-2 shows the basic idea.

Ruby is an example of a *solid-state laser*, in which light-emitting atoms are distributed in a transparent solid. In ruby, the transparent material is sapphire (aluminum oxide or Al_2O_3) and the light-emitting atoms are chromium. Such transparent solids do not conduct electric current, so the light-emitting atoms must be excited by light from an external source, such as a flash lamp or another laser, a process called *optical pumping*. Typically small quantities of light-emitting elements such as neodymium, erbium, and ytterbium are added to transparent crystals, glasses, and ceramics, which are shaped into rods, thin disks, slabs, or optical fibers for use in lasers.

Some solid-state lasers are excited with flash lamps or with bright lamps that emit continuously. Others are excited by light from other lasers, usually semiconductor diodes. Chapter 8 describes solid-state lasers in more detail. Chapter 9 describes fiber

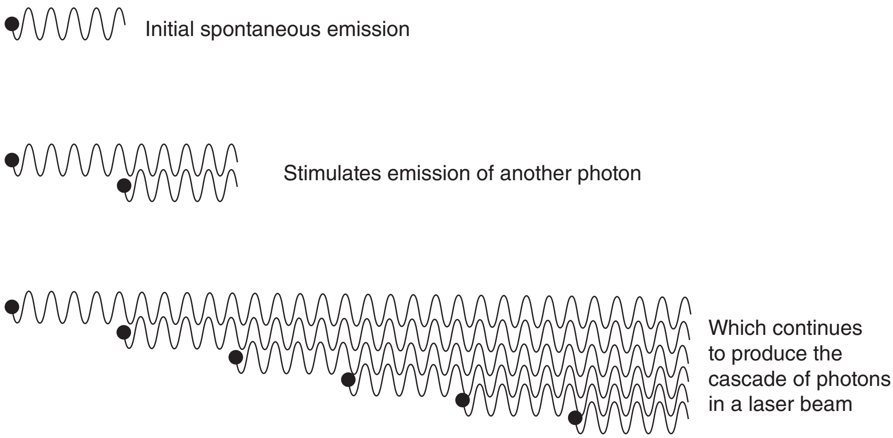

Figure 1-2. A single spontaneously emitted photon triggers stimulated emission from excited atoms, building up a cascade of stimulated emission. In ruby, the excited atoms are chromium.

lasers, a type of solid-state laser distinct and important enough to deserve their own chapter.

A second broad class of lasers are *gas lasers,* covered in Chapter 7, in which a light-emitting gas or vapor is confined inside a hollow tube with mirrors on the ends. Passing an electric discharge through the gas excites the atoms to states in which they can generate stimulated emission. Important examples are the helium–neon, rare-gas-halide and carbon dioxide lasers, described in more detail in Chapter 7. Gas lasers have been replaced by solid-state lasers for many applications but remain in use for others.

A third broad class are *semiconductor lasers,* which, in the laser world, are considered distinct from solid-state lasers. Most semiconductor lasers are called *diode lasers* or *laser diodes* because they have two electrical terminals, and current flows in only one direction between the terminals to generate stimulated emission inside the semiconductor, as you will learn in Chapter 10. Semiconductor lasers are versatile devices that can play many roles in laser technology. Some are tiny, cheap, and low-power devices used in CD, DVD, and Blu-Ray players, and laser pointers. Others are larger devices that emit hundreds of watts and can convert more than half of the electrical energy passing through them into light, for use in pumping solid-state lasers or in some industrial applications.

Chapter 11 describes a few lasers that have found important applications but do not fall into the broad categories of gas, solid-state, fiber, or semiconductor lasers. It also covers a number of light sources that generate laser-like light but do not exactly fall under the definition of lasers. Many are nonlinear devices that shift laser light to other wavelengths in various ways.

1.5 OPTICAL PROPERTIES OF LASER LIGHT

The practical importance of lasers comes from the unusual properties of light in a laser beam. These properties are crucial for applications of lasers ranging from cutting sheets of plastic or metal to making extremely precise and sensitive measurements in scientific research. The most important of these optical properties are:

- Wavelength(s)
- Beam power and energy
- Variation of beam power with time (e.g., pulse duration)
- Beam divergence and size
- Coherence
- Efficiency

1.5.1 Wavelength(s)

Most lasers are called *monochromatic*, meaning single-colored, but that single wavelength generally can be adjusted a little or a lot, depending on the light-emitting material in the laser and on the optics used in the laser. The laser material determines the range of possible wavelengths; the optics select which of those the laser emits. The details can become complicated and are covered in Chapters 3 and 4.

Lasers typically operate in the ultraviolet, visible, and infrared parts of the spectrum. Table 1-1 lists some important lasers emitting in that range, their primary wavelengths, and the chapters that describe them. In addition, it is possible to generate additional wavelengths from these lasers, some of which can be quite important, such as the 532-nanometer green line produced by generating the second harmonic of the 1064-nm line of neodymium, as described in Section 5.6. Thousands of other laser lines have been demonstrated in the laboratory, but most are not used regularly.

Table 1-1. Some important lasers and their wavelengths

Laser name and type	Wavelengths	Chapter
Argon fluoride (ArF) gas, excimer	193 nm	7
Krypton fluoride (KrF) gas, excimer	248 nm	7
Organic dye, liquid	320–1000 nm	11
Nitride diode (InGaN), semiconductor	375–525 nm	10
Argon ion, gas	488, 514.5 nm	7
Helium–neon, gas	632.8 nm	7
InGaAlP, semiconductor	635–660 nm	10
GaAsP, semiconductor	670 nm	10
Titanium–sapphire, solid-state	700–1000 nm	8
GaAs/GaAlAs, semiconductor	780–905 nm	10
InGaAs, semiconductor	915–980 nm	10
Ytterbium, fiber, solid-state	1030–1080 nm	9
Neodymium, solid-state	1060, 1064 nm	8
InGaAsP, semiconductor	1150–1650 nm	10
Erbium, fiber, solid-state	1530–1600 nm	8, 9
Quantum cascade, semiconductor	4–12 μm	10
Carbon dioxide (CO_2)	9–11 μm	7

1.5.2 Beam Power, Energy, and Intensity

Power is a critical quantity for laser beams, and it can be measured in three different ways that give distinctly different information.

Power measures the rate of energy delivery by a laser beam. It is important to remember that power is the amount of energy delivered per unit time. It is defined by the formula:

$$\text{Power} = \frac{\Delta\ \text{energy}}{\Delta\ \text{time}} \tag{1-1}$$

One *watt* of power equals one *joule* (of energy) per second. Strictly speaking, power measures how fast energy is being delivered at any given instant, so it varies with time for pulsed lasers, but is nominally constant for continuous lasers. If a laser emits a series of pulses, it can also be measured by its *average power*, the sum of the pulse energies divided by the time covered. The powers of continuous laser beams range from less than a milliwatt (0.001 watt) to over a hundred kilowatts (100,000 W), and the average powers of repetitively pulsed lasers are similar. *Peak power* measures the maximum rate of power delivery during a laser pulse and can reach much higher levels.

Energy in joules measures the total amount of energy delivered during an interval. Typically, it measures the energy delivered by a single laser pulse. The shorter the time the laser takes to deliver a given energy, the higher the peak power.

Intensity measures the power deposited per unit area. The smaller the laser spot, the higher the intensity and the more it affects what it illuminates. Think of how bright sunlight may warm a piece of paper, but focusing sunlight through a magnifier can heat the paper so it burns in a small spot.

All of these quantities are important and will be discussed in more detail later.

1.5.3 Laser Variations in Time

Some lasers can emit continuous beams, but others are limited to emitting pulses because of their internal physics. Continuous lasers can be turned on and off by modulating their output in some way. The details differ among laser types, and we will explain them when we cover the individual laser types. Inherently pulsed lasers typically fire a series of pulses at regular intervals, but some fire only a single laser shot at a time.

The length of laser pulses can vary widely, ranging from milliseconds (10^{-3} second) to femtoseconds (10^{-15} second). The pulse timing and spacing may depend on the physics of the laser, but these can also be controlled by the operator. One approach is to modulate the input power so the laser switches on and off, as when you turn a laser pointer on and off. Another way to control output is by using optical accessories described in Chapter 5. Modulating laser output can be very important and will be explained later in this book.

1.5.4 Beam Appearance, Divergence, and Size

You cannot see a laser beam in the air unless something reflects the light toward you, such as smoke or fog in the air or the beam hitting a wall or your hand. When the beam emerges from the laser, it has a diameter that depends on the size of the output optics. For small lasers such as red laser pointers, this typically is a millimeter or two and looks as thin as a string or a pencil line.

Although a laser beam looks straight to your eyes, it actually spreads at a very small angle, called the *divergence,* which is shown in Figure 1-3. The divergence depends both on the type of the laser

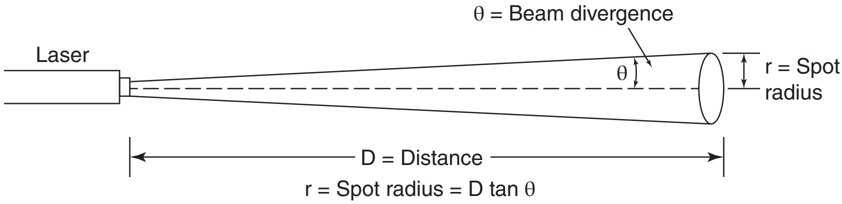

Figure 1-3. Calculating the size of a laser spot from the beam divergence.

and on the external optics. Most semiconductor lasers have beams that spread widely, but laser pointers typically have optics added to focus the beam into a narrow pencil-like beam.

Typically, laser beam divergence is measured in thousandths of a radian, a milliradian, a unit equal to 0.057 degree. As long as the beam divergence is small, you can estimate the radius of a laser spot at a distance *D* from the laser by multiplying the distance by the divergence in radians. Thus, a 2-milliradian beam spreads to a 0.2 meter spot at a distance of 100 meters. This high directionality of the laser beam is important for many applications.

1.5.5 Coherence

Stimulated emission makes laser light coherent because output photons have the same wavelength and phase as the input photons that stimulate emission. This makes laser light *coherent*, with the peaks and valleys of the waves marching in phase like soldiers on parade. Figure 1-4 compares coherent and incoherent light. The peaks and valleys of coherent light waves (top of Figure 1-4) are all the same length and have their peaks and valleys aligned. The peaks and valleys of incoherent light waves (bottom of Figure 1-4) do not line up. Laser light gets its coherence from stimulated emission. The sun, light bulbs, flames, and most other sources generate spontaneous emission, and their output is incoherent.

The degree of coherence depends on the range of wavelengths emitted, which differs among lasers. A laser that emits only a single wavelength, called *monochromatic*, generally is more coherent than a laser emitting a broader range of colors. Monochromatic light need not be coherent, but light that is not monochromatic cannot stay coherent over a long distance. Lasers are the only light sources that can readily generate light that is coherent over relatively long distances of centimeters and up.

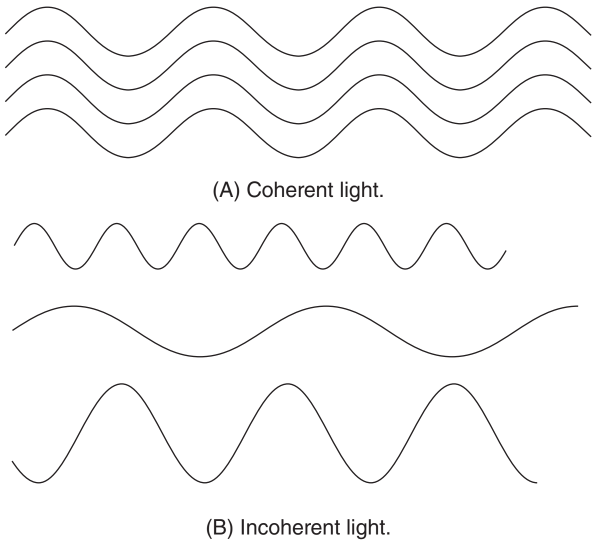

Figure 1-4. Coherent (A) and incoherent (B) light.

1.5.6 Energy Conversion Efficiency

Lasers convert other forms of energy into laser light. This conversion efficiency can be very important for some laser applications, and many advances of recent years come from improvements in efficiency. In some early gas lasers, as little as 0.001% of the electrical power that went into the laser emerged as light in the output beam. What made the laser light valuable was that its beam was tightly focused, coherent, and monochromatic.

Many modern lasers convert 10% to 70% of input energy into laser light, and that is vital for applications that require large amounts of laser power, such as cutting and welding metals, or exciting other lasers. Semiconductor diode lasers can convert as much as 70% of the electrical energy passing through them into light. Solid-state fiber lasers can convert over 70% of the light energy powering them into a high-quality laser beam, making them particularly well suited for industrial machining applications.

1.6 HOW LASERS ARE USED?

Scientists and engineers began playing with lasers almost as soon as they could lay their hands on them. They fired laser pulses at just about everything that could not run away. They shot so many holes in razor blades that for a while laser power was informally measured in "gillettes." Yet few practical applications emerged quickly, and for a while the laser seemed to be, as Irnee D'Haenens told Ted Maiman soon after they made the first one, "a solution looking for a problem."

We are long past that stage. Lasers have become standard tools in industry and research. They align construction equipment, transmit voice and data around the globe, and perform exquisitely sensitive measurements that have earned a fair number of Nobel Prizes. Table 1-2 lists some laser applications, and Chapters 12–14 cover laser applications in more detail.

Lasers are used in diverse ways. The final three chapters divide laser applications into three broad categories.

Chapter 12 covers low-power applications. One broad family of such applications uses lasers as sources of highly controlled light for transmitting and processing information, such as reading or writing data or transmitting signals. Laser light transmitted through hair-thin optical fibers is the backbone of the global telecommunications network; it carries phone calls from the cell tower nearest you to anywhere around the world. Lasers inside optical disk players read music from CDs and videos on DVDs and Blu-Ray disks. The coherence of lasers makes it possible to create and display three-dimensional holographic images.

Another broad category of low-power applications is measurement. Laser beams can draw straight lines in space to help construction workers align walls or pipes. Precision techniques use the coherence of lasers to measure distances to within a fraction of the wavelength of light. Laser radars can create three-dimensional profiles of our environment, digitizing dinosaur fossils for paleontologists and helping to steer self-driving cars away from potential roadside hazards.

Chapter 13 covers high-power applications, in which a laser beam delivers energy that alters the material it hits. Lasers deliver small bursts of energy to mark painted metal surfaces; the laser vaporizes the paint, exposing the shiny metal. More powerful lasers can drill holes through materials ranging from baby-bottle nipples to sheets of titanium. The laser beam does not bend soft materials like latex nipples and does not grow dull like a drill bit cutting into a hard material.

Laser surgery works in the same way. Pulses from an ultraviolet laser can vaporize tissue from the lens of the eye, precisely removing just the right amount to correct vision defects. By selecting

Table 1-2. A sampling of laser applications

Information handling
Fiber-optic communications
Laser printers for computer output
Playing DVD or Blu-Ray video
Playing CD audio
Reading and writing computer data on CDs and DVDs
Reading printed bar codes for store checkout and inventory control
Measurement and inspection
Exciting fluorescence from various materials
Illuminating cells for biomedical measurements
Measuring concentrations of chemicals or pollutants
Measuring small distances very precisely
Measuring the range to distant objects
Measuring velocity
Projecting straight lines for construction alignment and irrigation
Studies of atomic and molecular physics
Helping guide self-driving cars
Medicine and dentistry
Bleaching of port-wine stain birthmarks and certain tattoos
Clearing vision complications after cataract surgery
Dentistry
Refractive surgery to correct vision
Reattaching detached retinas
Shattering of stones in the kidney and pancreas
Treatment of diabetic retinopathy to forestall blindness
Surgery on tissue rich in blood vessels
Materials working
Cutting, drilling, and welding plastics, metals, and other materials
Cutting titanium sheets
Non-contact machining
Drilling materials from diamonds to baby-bottle nipples
Engraving wood
Heat-treating surfaces
Marking identification codes
Semiconductor photolithography
Three-dimensional printing or additive manufacturing
Military
Range-finding to targets
Simulating effects of nuclear weapons
Target designation for bombs and missiles
War games and battle simulation
Antisatellite weapons
Anti-sensor and antipersonnel weapons
Defense against rockets, artillery, mortars, drones, and small boats

Table 1-2. (*Continued*)

Other applications
Basic research
Controlling chemical reactions
Theater displays
Holography
Laser light shows
Laser pointers
Laser paint removal from aircraft

the right laser wavelength, surgeons can bleach dark birthmarks or tattoos.

The ultimate in high-power lasers are high-energy laser weapons. You can think of them as performing materials working on unfriendly objects. A laser weapon might blind the sensor that guides a missile, causing it to go astray. Or a higher-energy laser weapon can heat explosives in a rocket to their detonation temperature, soften high-pressure fuel tanks so they fail, or ignite gasoline fumes to catch an engine on fire. Lasers can also detonate unexploded shells left on a battlefield, or defend ships against attacks by drones or small boats.

Chapter 14 covers laser applications in scientific research. Laser techniques can slow atoms to a virtual crawl and probe their energy states with exquisite precision. Laser beams can manipulate tiny objects, from bacteria to single atoms. These laser applications have led to many Nobel Prizes.

1.7 WHAT HAVE WE LEARNED?

- Optics is the science of light. Photonics is another term for optics, usually covering devices that work on photons rather than on light waves.
- LASER is an acronym for “light amplification by the stimulated emission of radiation.”
- Stimulated emission of light by excited atoms generates laser radiation.
- Most lasers are tiny semiconductor chips.
- Lasers have become so commonplace in many places.
- Charles Townes conceived of the amplification of stimulated emission for microwaves.

- Theodore Maiman demonstrated the first laser using a ruby rod pumped by a photographic flashlamp.
- Successful operation of a laser requires both an optical resonator and a suitable gain medium to amplify light.
- The three main classes of lasers are gas, semiconductor, and solid-state lasers.
- Fiber lasers are a type of solid-state laser in which the laser is an optical fiber.
- Solid-state is not equivalent to semiconductor in the laser world.
- Lasers can emit a very narrow range of wavelengths.
- Laser light is concentrated in a beam, which is generally tightly focused.
- Laser light is coherent.
- Low-power laser applications include measurement and information processing.
- High-power laser applications modify materials for tasks including surgery, machining, and weapons.
- Lasers can make precision measurements for scientific research.

WHAT'S NEXT?

The first step in understanding lasers is to learn the basic principles of physics and optics that are involved in laser operation. Chapter 2 introduces the essential physical concepts. Some of this material may be familiar if you have been exposed to physics, but you should review it because later chapters assume that you understand it.

QUIZ FOR CHAPTER 1

1. The word laser originated as
   a. A military code word for a top-secret project
   b. A trade name
   c. An acronym for Light Amplification by the Stimulated Emission of Radiation
   d. The German word for light emitter
2. Which statement is not true
   a. Light sometimes acts as a wave and sometimes acts as a photon
   b. Only laser light acts as photons
   c. Light is a form of electromagnetic radiation

d. Visible light differs from ultraviolet in wavelength
e. Electromagnetic radiation includes radio waves

3. Most lasers today are
   a. Semiconductor devices used in electronic equipment
   b. High-power weapons used to deter drone attacks
   c. Gas-filled tubes emitting red light
   d. Ruby rods powered by flash lamps
   e. Ruby rods powered by LEDs
4. Laser light is generated by
   a. Spontaneous emission
   b. Gravity
   c. Stimulated emission
   d. Microwaves
   e. Mirrors
5. What emits light in a ruby laser?
   a. Aluminum atoms
   b. Sapphire atoms
   c. Oxygen atoms
   d. Chromium atoms
   e. Mirrors on the ends of the rod
6. Why are most semiconductor lasers sometimes often called diode lasers?
   a. Because the first diode lasers had to be installed in vacuum tubes so the semiconductor would not evaporate.
   b. Because they conduct light between two terminals to generate stimulated emission.
   c. Because it is powered by light from an external light-emitting diode.
   d. Because it is an acronym for "damn idiotic optical device exploded," which is what happened to the first one.
7. You have a laser that emits one watt of light and is 1% efficient. How much of the input power ends up as heat rather than light?
   a. One watt
   b. Three watts
   c. 10 watts
   d. 30 watts
   e. 99 watts
8. You have a laser that emits one watt of light and is 25% efficient. How much of the input power ends up as heat rather than light?
   a. One watt
   b. Three watts

   c. 10 watts
   d. 30 watts
   e. 99 watts
9. Stimulated emission generates light waves that are in phase with each other. This makes them
   a. A beam
   b. Coherent
   c. Pulsed
   d. Span a range of wavelengths
10. How many lasers do you own? There is no single "right" answer, but it can be fun to take a mental inventory. Do not forget that some devices may contain multiple lasers, such as a Blu-Ray player that can also play DVDs and CDs.

CHAPTER 2

PHYSICAL BASICS

ABOUT THIS CHAPTER

Lasers evolved from concepts of modern physics that emerged early in the 20th century. To understand lasers, you need to understand basic concepts including light, atomic energy levels, quantum mechanics, and optics. This chapter starts with the nature of light, then moves on to how light is generated, the interactions of light and matter, and some fundamentals of optics and fiber optics, to give you the background you need to understand lasers themselves.

2.1 ELECTROMAGNETIC WAVES AND PHOTONS

Early physicists debated long and loud over the nature of light. In the 17th century, Christian Huygens believed light was made up of waves, but Isaac Newton held that light was made up of tiny particles. Newton's theory was thought to be right for a century, until Thomas Young showed the interference of light, which could only be explained by waves.

Today, we know that both theories are partially right. Much of the time, light behaves like a wave. Light is called an *electromagnetic* wave because it consists of electric and magnetic fields perpendicular to each other, as shown in Figure 2-1. Because the electric and magnetic fields oscillate perpendicular to the direction in which the waves travel, they are called *transverse waves.*

Understanding Lasers: An Entry-Level Guide, Fourth Edition. Jeff Hecht.

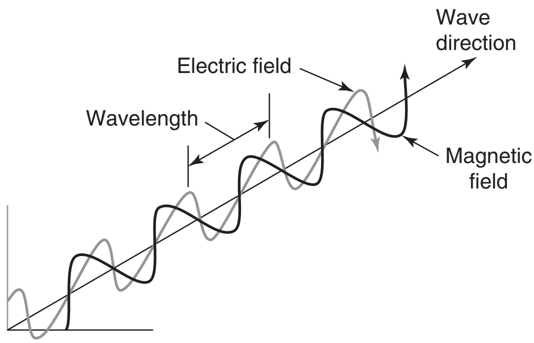

Figure 2-1. Structure of an electromagnetic wave.

At other times, light behaves like massless particles called *photons.* A photon is a quantum of electromagnetic energy, not the hard particle that Newton envisioned. The quantum view that light comes in discrete chunks rather than a continuous wave is also critical to understanding light. We will move back and forth between the wave and particle views of light, but you should remember that they are just different ways to look at the same thing. We also include some simple formulas, explaining them in words to help you understand what they mean. You should remember these ideas if you have had a physics course.

2.1.1 Waves and Photons

We describe electromagnetic waves by one of two related values. The *wavelength* is the distance between successive peaks, shown in Figure 2-1, and denoted by the Greek letter lambda (λ). The *frequency* is the number of wave peaks passing a point in a second, denoted by the Greek letter nu (ν). Frequency is measured in oscillations (from peak to valley and back) per second, a unit called hertz, after Heinrich Hertz, the 19th-century discoverer of radio waves. Multiplying the wavelength by the number of waves per second gives the wave velocity, as a distance per second:

$$\text{Wavelength} \times \text{Frequency} = \text{Velocity} \tag{2-1}$$

The velocity of light and other electromagnetic waves is a universal constant, denoted by *c,* the speed of light in vacuum, which is close to 300,000 kilometers per second or 186,000 miles per second. (The exact value is 2.99792458×10^8 meters/second, listed in Appendix C, but the round number usually is good enough for practical purposes.) This means the shorter the wavelength, the higher the frequency. Using the standard symbols for wavelength, frequency, and the speed of light, we can write simple formulas to convert between wavelength and frequency in a vacuum:

$$\lambda = c/\nu \tag{2-2}$$

and

$$\nu = c/\lambda \tag{2-3}$$

We can also view light as *photons* or *quanta,* massless particles that travel at the speed of light. The energy of a photon E equals the frequency of the wave multiplied by a constant h, which is called *Planck's constant* after the German physicist Max Planck, who worked out the formula. Planck's constant equals 6.63×10^{-34} joule-second, so photon energy is

$$E = h\nu = 6.63 \times 10^{-34}\,\nu \tag{2-4}$$

The frequency ν is measured in waves per second, so multiplying it by the number of waves (sometimes called cycles) gives energy per photon in the same joule-second units as Planck's constant.

You can use this formula and the relationship between wavelength and frequency to show that wavelength times photon energy equals Planck's constant multiplied by the speed of light c, or 1.99×10^{-25} joule-meter:

$$\lambda E = hc = 1.99 \times 10^{-25} \text{ joule-meter} \tag{2-5}$$

You may need these conversion factors from time to time when you work with light and other electromagnetic waves, so they are listed in Appendix B. For now, the most important lesson is that the nature of a light wave can be measured in three ways: photon energy, wavelength, or frequency. For example, light with a 1-μm wavelength roughly has a frequency of 3×10^{14} Hz, and photon energy of 2×10^{-19} joule.

Physicists often measure photon energy in electron volts, the energy an electron acquires by moving through a one-volt potential. One electron volt equals 1.6022×10^{-19} joule, so a photon energy of

2×10^{-19} joule equals 1.24 electron volts, a more convenient unit of measurement.

It is easy to make mistakes in converting units, so it helps to remember these simple rules of thumb:

- The higher the frequency, the shorter the wavelength.
- The higher the frequency, the larger the photon energy.
- The shorter the wavelength, the larger the photon energy.

Electromagnetic waves are often called *electromagnetic radiation* because objects emit or *radiate* them into space. If the word "radiation" sounds distressingly like something that comes from a leaky nuclear reactor, it is. However, that loses the vital difference between nuclear and electromagnetic radiation. The electromagnetic spectrum spans a broad range of photon energies, and only the most energetic photons—X-rays and gamma rays, which have the highest frequencies and shortest wavelengths—pose any radiological threat. Ultraviolet light with longer wavelengths and less energy can cause sunburn with long-term risk of skin cancer.

2.1.2 The Electromagnetic Spectrum

We usually think of the spectrum as the colors we see in a rainbow or those that appear when we pass sunlight through a prism. Colors are the way our eyes and brains sense the differences in wavelength across the visible spectrum, from the short violet waves to the long red waves. However, our eyes can see only a narrow slice of the whole *electromagnetic spectrum.* Table 2-1 lists the components of

Table 2-1. Wavelengths and frequencies of electromagnetic radiation. Boundaries are approximate.

Name	Wavelengths (m)	Frequencies (Hz)
Gamma rays	under 3×10^{-11}	over 10^{20}
X-rays	3×10^{-11} to 10^{-8}	3×10^{16} to 10^{20}
Ultraviolet light	10^{-8} to 4×10^{-7}	7.5×10^{14} to 3×10^{16}
Visible light	4×10^{-7} to 7×10^{-7}	4.2×10^{14} to 7.5×10^{14}
Infrared light	7×10^{-7} to 10^{-3}	3×10^{11} to 4.2×10^{14}
Microwaves	10^{-3} to 0.3	10^{9} to 3×10^{11}
Radio waves	0.3 to 30,000	10^{4} to 10^{9}
Low-frequency waves	over 30,000	under 10,000

Table 2-2. Prefixes used for metric units. Note that abbreviations for mega and above are capital letters.

Prefix	Abbreviation	Meaning	Value
exa	E	quintillion	10^{18}
peta	P	quadrillion	10^{15}
tera	T	trillion	10^{12}
giga	G	billion	10^{9}
mega	M	million	10^{6}
kilo	k	thousand	1,000
deci	d	tenth	0.1
centi	c	hundredth	0.01
milli	m	thousandth	0.001
micro	μ	millionth	10^{-6}
nano	n	billionth	10^{-9}
pico	p	trillionth	10^{-12}
femto	f	quadrillionth	10^{-15}
atto	a	quintillionth	10^{-18}

that spectrum, ranging from extremely low-frequency waves many miles long to gamma rays less than a trillionth of a meter long.

Table 2-1 lists all frequency and wavelength values in scientific units to simplify comparison over orders of magnitude. In practice, the values of frequency, wavelength, and other quantities such as time and power are expressed in metric units with the standard prefixes shown in Table 2-2. You probably already know some of these prefixes, but you are likely to discover others as you explore the world of lasers. Virtually everything optical is measured in metric units, and this book follows that practice. (Some older books give visible wavelengths in Ångstroms, Å, a unit equal to 10^{-10} meter or 0.1 nanometer, but the Ångstrom is not a standard metric unit.)

Parts of the electromagnetic spectrum were discovered at different times, and the boundaries between them remain poorly defined. Radio waves, X-rays, and gamma rays were discovered separately, and only later did physicists realize that all were electromagnetic waves. Even the limits of human visibility are not rigidly defined because the eye's sensitivity drops slowly at the red and violet ends of the spectrum, as shown in Figure 2-2. The human visible range usually is defined as 400 to 700 nanometers, but the human eye can faintly sense wavelengths from 380 to 780 nm.

In practice, the terms "light" and "optical" are not limited to visible wavelengths. Parts of the infrared and ultraviolet are also

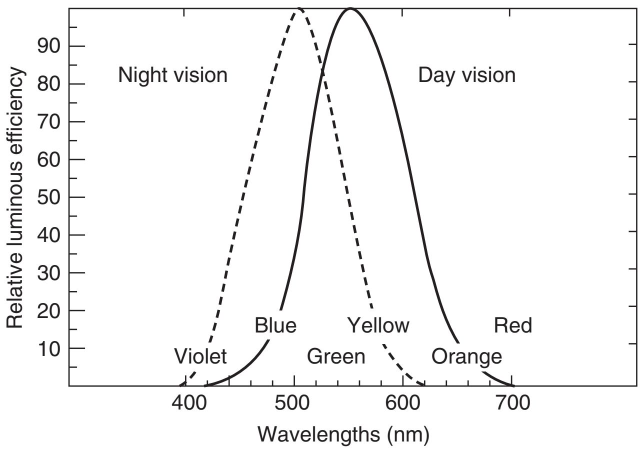

Figure 2-2. Relative sensitivity of the human eye to different wavelengths during daylight when we see colors, and at night when only one visual receptor is active.

called optical or light because those invisible wavelengths act much like visible light.

The electromagnetic spectrum is a continuum spanning many orders of magnitude in frequency and wavelength. The divisions that we make depend largely on how waves in different parts of the spectrum interact with matter. For example, wavelengths shorter than about 200 nm are called "vacuum ultraviolet" because air absorbs them so strongly that they must be observed in a vacuum. Section 2.3 tells more about how light interacts with matter.

Lasers normally operate in the infrared, visible, and ultraviolet bands. Masers, the microwave counterparts of lasers, operate at microwave frequencies, which are lower than those in the infrared. The few research lasers that operate in the X-ray band are described in Sections 11.6 and 14.11.

2.1.3 Interference and Waves

As you learned in Section 2.1.1, light has a dual personality, sometimes behaving as waves and sometimes as particles. The best illustration of the wave nature of light is the interference of waves seen when light from one source passes through two parallel slits. As shown in Figure 2-3, waves emerging from the two slits combine to form a pattern of alternating light and dark bands. That pattern

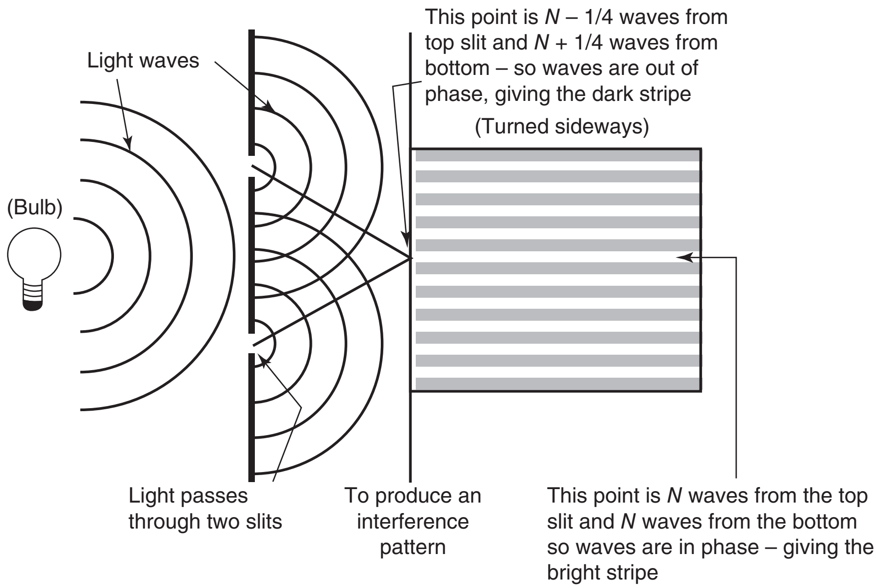

Figure 2-3. Bright light illuminating two slits causes interference.

comes from adding the amplitudes of the waves emerging from the two slits when they reach the screen at the back. The light is bright where two peaks or two valleys overlap and add together, a process called *constructive interference*. But the light vanishes where a peak of one wave meets a valley of the other, so they cancel each other to leave no light, a process called *destructive interference.* Figure 2-4 shows how the two waves add up in both cases.

Interference is a general effect and occurs whenever waves combine. If the two waves are precisely in phase, they add together without loss. If two equal-amplitude waves are exactly one-half wavelength (180 degrees) out of phase, they cancel each other out at that point. In either case, the waves keep on going unless something blocks them, so they can interfere with other waves at other points in space.

No light energy is really lost in destructive interference. If nothing blocks the waves, they just keep on going as if they had never encountered each other, like ripples spreading across a pond. If something does block the light so you see a pattern of light and dark zones, the total amount of energy across the pattern remains the same, but interference changes its distribution.

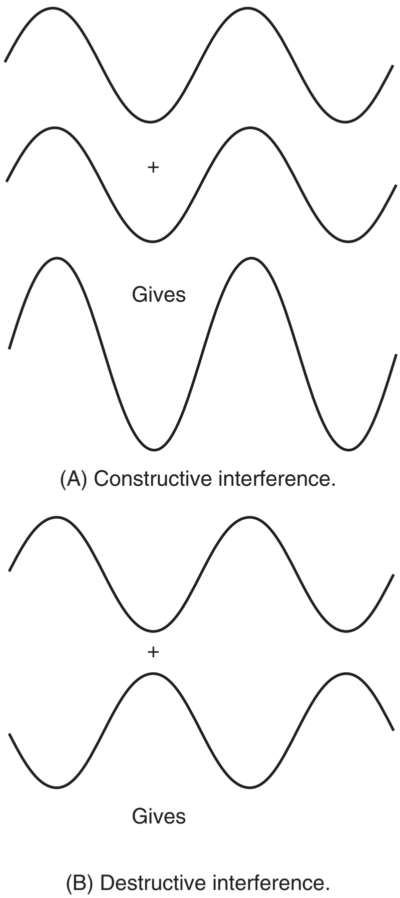

Figure 2-4. Addition and subtraction of light-wave amplitudes causes interference. (A) Constructive interference. (B) Destructive interference.

Interference is a very important property of light, and it is particularly important for lasers because their coherent light remains in phase over relatively long distances.

2.1.4 Light as Photons

The photon side of light's dual personality shows most clearly when light interacts with matter.

One of the most famous examples is called the *photoelectric effect,* which causes certain metals to emit electrons if light strikes them in a vacuum. Initial experiments were puzzling because they showed a peculiar dependence on the wavelength. The metal did not emit electrons when illuminated by long wavelengths, even if the light was very bright. But at wavelengths shorter than a threshold level that differed among metals, the metal emitted a number of electrons that depended on the light intensity. That is, doubling the illumination doubled the number of electrons released.

This did not make sense if light was purely a wave; adding more energy at a long wavelength eventually should build up enough energy to free an electron. But in 1905, Albert Einstein explained that the threshold occurred because light energy was bundled as photons, and the photons had to have enough energy to free the electrons. Once you had a wavelength short enough to get a photon with enough energy to free the electron, adding more light could free more electrons. Einstein's explanation of the photoelectric effect helped lay the groundwork for quantum mechanics, and it eventually earned him the Nobel Prize in Physics.

2.2 QUANTUM AND CLASSICAL PHYSICS

So far, we have mostly considered light, but laser physics is not just about light; it is about how we use matter to produce a beam of coherent light. That means we need to look at quantum mechanics and the atom.

The operation of a laser depends on the quantum mechanical properties of matter. The classical physics described by Isaac Newton assumed that energy could vary continuously, like an absolutely smooth liquid. In contrast, quantum mechanics tells us that energy comes in discrete chunks called *quanta*, so everything in the universe can have only discrete amounts of energy. In classical physics, energy can change continuously; in quantum mechanics, it changes in steps. The wave picture of light is classical; the photon picture is quantum mechanical.

The central concern for the laser is the quantization of energy levels within atoms. We will start with atomic energy levels, then look at how that leads to the atomic physics behind the laser.

2.2.1 Energy Levels

The simplest atom is hydrogen, in which one electron circles a nucleus that contains one proton. The hydrogen atom looks like

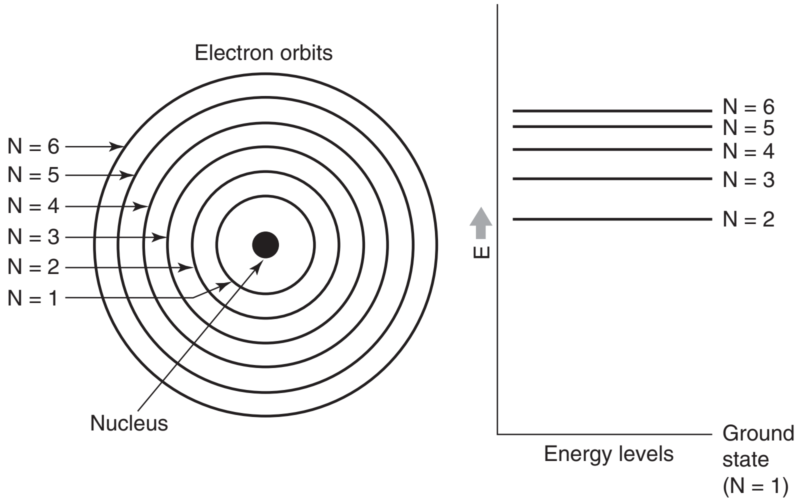

Figure 2-5. Electron orbits and the corresponding energy levels of the hydrogen atom.

a very simple solar system, with a single planet (the electron) orbiting a star (the proton). The force holding the atom together is not gravity but the electrical attraction between the positive charge of the proton and the negative charge of the electron.

In a real planetary system, the planet could orbit at any distance from the star. However, quantum mechanics allows the electron in the hydrogen atom to occupy only certain orbits, shown in Figure 2-5. We show the orbits as circles for simplicity, but we cannot see the exact shape of the orbits. Their nominal sizes depend on a “wavelength” assigned to the electron because matter, too, sometimes can act like a wave. The circumference of the innermost orbit equals one wavelength, the next orbit equals two wavelengths, and so on.

If we added energy to a planet, it would speed up and move further from its star. The electron in a hydrogen atom can also move to more distant orbits when it absorbs extra energy. However, unlike a planet, the electron can occupy only certain orbits, usually called energy levels, which are plotted at the side of Figure 2-5, with labels indicating the corresponding orbits. The atom is in its lowest possible energy level—the ground state—when the electron is in the innermost orbit, closest to the proton. (The electron cannot fall onto the proton.)

The spacing between energy levels in the hydrogen atom decreases as the energy levels become higher above the ground state and, eventually, the energy difference becomes vanishingly small. If the electron gets enough energy, it escapes from the atom altogether, a process called *ionization*.

Physicists often define the energy of an ionized hydrogen atom as zero so they can write the energy of the un-ionized hydrogen atom E as a negative number using the simple formula

$$E = -R/n^2 \tag{2-6}$$

where R is a constant (2.179×10^{-18} joule) and n is the quantum number of the orbit (counting outward, with one being the innermost level).

Hydrogen is the simplest atom in the universe, so physicists use it as a model to explain quantum mechanics and atomic energy levels. Naturally, things get considerably more complex in atoms with more electrons. Each electron occupies an energy state that is specified by multiple quantum numbers, which physicists interpret as identifying quantities including the shell, the subshell, position in a shell, and spin. You do not need to know the details to understand the basics of laser physics, so we will skip them.

One thing that is important is a rule called the Pauli exclusion principle, which says that each electron in an atom must occupy a unique quantum state, with a unique set of quantum numbers. Shells and subshells usually are identified by a number and letter, such as 1*s* or 2*p*. The number is the primary quantum number. The letter identifies subshells formed under complex quantum mechanical rules. Each shell can contain two or more electrons, but each electron must have a unique set of quantum numbers. In the simplest case of two-electron shells, the two electrons spin in opposite directions.

If atoms are in their ground state, electrons fill in energy levels from the lowest-energy or innermost shell until the number of electrons equals the number of protons in the nucleus. The primary quantum number of the last ground-state electron corresponds to the row the element occupies on the periodic table. Figure 2-6 shows how electrons fill up a series of energy levels for neodymium, which has an atomic number 60 and is widely used in lasers.

These energy levels are the same ones that play a crucial role in chemistry, determining the chemical behavior of the elements and

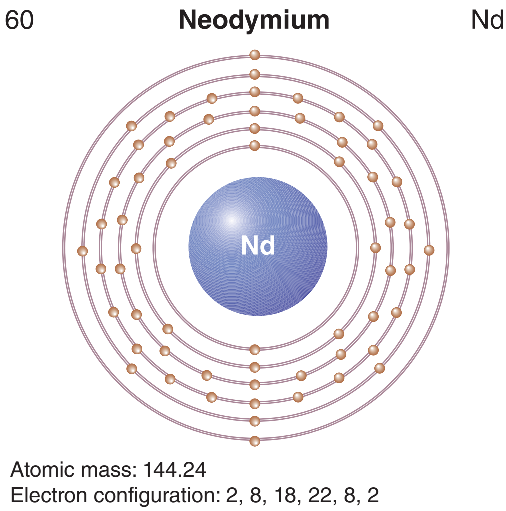

Figure 2-6. Electron shells of neodymium, which has 60 electrons. (iStock)

the structure of the periodic table. Electrons generally fill up the shells from the inside out, although it gets more complex for rare-earth elements like neodymium. In lasers, as in chemistry, the outermost electrons are the easiest ones to excite, and the extra energy takes them to higher energy levels not shown in Figure 2-6.

2.2.2 Transitions and Spectral Lines

The transitions that atoms and molecules make between energy levels are crucial to laser physics. To understand their importance, let us look again at the neodymium atom.

The electron needs an extra increment of energy to move from the ground state to a higher energy level. Conversely, the electron must release energy to drop from a higher level to a lower one. Electrons can do this by absorbing or emitting photons with energy equal to difference between the two states involved in the transition. (They can also transfer energy in other ways.)

To move one step up the energy-level ladder, an electron must absorb a photon with energy equal to the difference between the two levels, called the transition energy. To drop back down to the lower state, the electron must emit a photon with the same energy. These transition energies differ between pairs of levels.

For the simple case of hydrogen, this means that the atom's single electron can absorb or emit light only at wavelengths corresponding to transitions between the simple energy levels shown in Figure 2-5. Neodymium is considerably more complex. Most of the 60 electrons are close enough to the nucleus that they have little effect on the outermost electrons, and the laws of quantum mechanics let electrons make transitions only between certain energy levels, but neodymium still has far too many energy levels and transitions to show in full. Figure 2-7 simplifies the energy levels in neodymium in one crystalline host to show what happens in a laser. Light from an external source excites the neodymium atom to a higher level, shown at left. Neodymium has a number of higher-level states, so light at 808 nm can raise the electron to one excited level, and light at 750 nm can excite the electron to a higher level. (Light at shorter wavelengths can excite the electron to higher levels not shown.) Electrons excited to those two higher levels spontaneously release some energy and drop to the upper laser state, where they accumulate until they are stimulated to

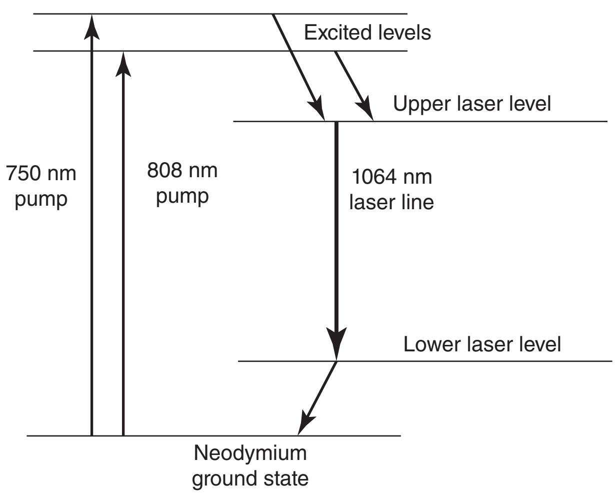

Figure 2-7. Laser action in neodymium. Light from an external source excites an electron in the outer shell of neodymium to a higher energy level, where it stays briefly before dropping to the upper laser level, which is long-lived, so many neodymium atoms wind up with electrons in that state. Stimulated emission then produces a cascade of light and the neodymium atoms drop down first to a lower laser level, then to the ground.

release their energy on the 1064-nm laser line, dropping to a lower energy level that is still not all the way down to the ground state.

The energy levels that electrons occupy in atoms are simple to describe, but there are also many more types of energy levels. Molecules, like atoms, have electronic energy levels, which increase in complexity with the number of electrons and atoms in the molecule. Molecules also have energy levels that depend on vibrations of atoms within them and on the rotation of the entire molecule. All these energy levels are quantized.

2.2.3 Types of Transitions

Atoms and molecules have many different types of energy-level transitions. Table 2-3 lists some important examples and their wavelength ranges.

Transitions like those of the neodymium atom are called *electronic transitions* because they involve electrons moving between two electronic energy levels. Specifically, they are transitions within the outer valence shell of electrons that are involved in chemical reactions. Hydrogen and helium only have one populated electron shell, so all their electrons are valence electrons, but heavier elements like neodymium also have electrons in inner shells, which do not take place in chemical reactions. Outer-shell transitions span a range of wavelengths from about 100 nm in

Table 2-3. Representative energy-level transitions and their wavelengths

Transition type	Wavelengths	Spectral range
Nuclear	0.0005–0.1 nm	Gamma ray
Inner-shell electronic (heavy element)	0.01–100 nm	X-ray
Inner-shell electronic (Cd^{+20})	13.2 nm	Soft X-ray
Electronic (Lyman-alpha in H)	121.6 nm	Ultraviolet
Electronic (argon-ion laser)	488 nm	Visible, green
Electronic (H, levels 2–3)	656 nm	Visible, red
Electronic (neodymium laser)	1064 nm	Near infrared
Vibrational (HF laser)	2.7 μm	Infrared
Vibrational (CO_2 laser)	10.6 μm	Infrared
Electronic Rydberg (H, levels 18–19)	0.288 mm	Far infrared
Rotational transitions	0.1–10 mm	Far infrared to microwave
Electronic Rydberg (H, levels 109–110)	6 cm	Microwave
Hyperfine transitions (Interstellar H gas)	21 cm	Microwave

the ultraviolet to a couple of micrometers in the near infrared. Electronic transitions can occur in molecules as well as atoms, although most electronic laser transitions are in atoms.

Transitions involving electron shells inside the valence shell of a heavy element have much higher energy than those of valence electrons. Inner-shell electrons are tightly bound to a highly charged nucleus, so ejecting them from the inner shell takes a lot of energy, and dropping back into the inner shell likewise releases a lot of energy. Laser action at wavelengths down to about 10 nm has been produced by blasting atoms with intense pulses of visible or infrared light that strip many electrons from the atoms, leaving a highly charged ion. Electrons that drop into inner shells emit short-wavelength photons. For example, blasting 20 electrons from cadmium atoms produces Cd^{+20}, which produces laser light at 13.2 nm when an electron falls back into the exposed inner shell.

In theory, transitions between energy levels in atomic nuclei could release gamma rays, photons with even more energy than X-rays, but no gamma-ray laser has been made.

On the other hand, very high-lying electronic energy levels (say, levels 18 and 19 of hydrogen) are spaced so closely that transitions between them involve very little energy, with wavelengths in the far infrared, microwave, or even radio-frequency range. These are called Rydberg transitions and can only occur under rare conditions.

Molecules have two other sets of quantized energy levels with lower energy than electronic transitions. Transitions involving vibrations of atoms in a molecule typically have wavelengths of a few to tens of micrometers. Those involving rotation of the entire molecule typically correspond to wavelengths of at least 100 μm. Laser action can occur in both vibrational and rotational transitions.

Transitions in two or more types of energy levels can occur at once. For example, a molecule can undergo a vibrational and a rotational transition simultaneously, with the resulting wavelength close to that of the more energetic vibrational transition. Many infrared lasers emit families of closely spaced wavelengths on such vibrational–rotational transitions. Molecules that make vibrational transitions generally make rotational transitions at the same time, which can spread the combined transition over a range of wavelengths.

Transition energies or frequencies add together in a straightforward manner:

$$E_{1+2} = E_1 + E_2 \tag{2-7}$$

where E_{1+2} is the combined transition energy, and E_1 and E_2 are the energies of the separate transition. The same rule holds if you substitute frequency ν for energy. However, you need a different rule to get the wavelengths of combined transitions:

$$\frac{1}{\lambda_{1+2}} = \frac{1}{\lambda_1} + \frac{1}{\lambda_2} \tag{2-8}$$

2.2.4 Absorption

For an atom to make a transition to a higher energy level, it must absorb a photon of the right energy to raise it to that higher energy level. You may think it unlikely that a photon of exactly the right energy would wander by just when an atom is in the right state to absorb it. In fact, it is not improbable because of other details we have not explained.

One is that atoms tend to occupy the lowest possible energy state, especially at cold temperatures. Hydrogen atoms floating in intergalactic space are likely to be cold and in the ground state, so they are prepared to absorb light. Sure enough, spectra of light from distant galaxies show dark lines where interstellar hydrogen atoms in the ground state absorbed the light.

A second is that atoms around us rarely are truly isolated. Atoms and molecules in the air are moving constantly, bumping into each other, and transferring energy. Atoms in solids and liquids are constantly in contact with their neighbors, transferring energy back and forth. An atom in a solid does not have to wait for a photon with exactly the right energy to match a transition; if the energy is close, the atom can transfer some energy to or from a neighbor to match the transition energy. As a result, absorption is not sharply defined when matter is packed together.

2.2.5 Stimulated and Spontaneous Emission

Light emission seems simpler than absorption. An atom in a high-energy state can make a transition to a lower state whenever it "wants to" simply by spontaneously emitting a photon of the right energy. Spontaneous emission, shown in Figure 2-8A, produces the

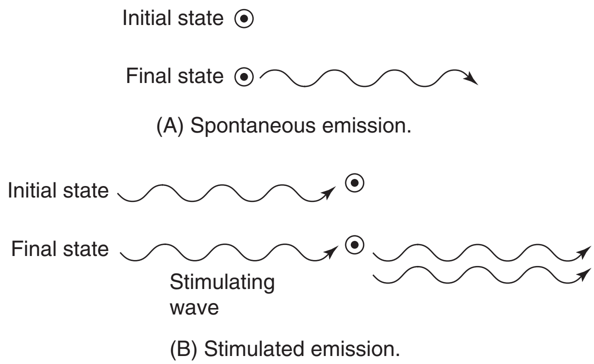

Figure 2-8. Spontaneous and stimulated emission.

light we see from the sun, stars, television sets, candles, and light bulbs. An atom or molecule in an excited state releases energy and drops to a lower energy state. On average, it releases the excess energy after a characteristic spontaneous emission lifetime (t_{sp}), which like the half-life of a radioactive isotope measures the time it takes half the excited atoms to drop to a lower state. No outside intervention is needed.

Albert Einstein recognized another possibility. A photon with the same energy as the transition could stimulate an excited atom to release its energy as a second photon with exactly the same energy. That second photon would be a wave with precisely the same wavelength as the first and would be precisely in phase with the stimulating photon, as shown in Figure 2-8B. You can visualize the process as a wave tickling the excited atom so it oscillates at the transition energy, increasing the chance it will release a second identical photon by stimulated emission.

Now we are almost at the point of having a laser. You learned earlier that “laser” was coined as an acronym for “Light Amplification by the Stimulated Emission of Radiation.” We have seen that, like a laser beam, stimulated emission is all at the same wavelength and in phase, or coherent. But we have not made a laser beam yet. It took decades for physicists to clear the crucial hurdle needed to amplify stimulated emission.

2.2.6 Populations and Population Inversions

The problem with stimulated emission is that it does not work well when matter is in *thermodynamic equilibrium,* a state in which

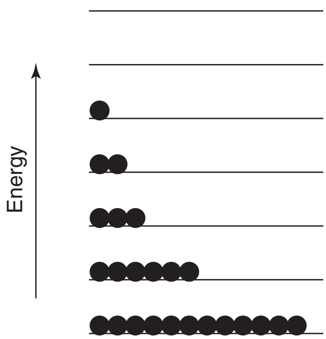

Figure 2-9. Relative populations of energy levels as a function of energy above the ground state at thermal equilibrium.

atoms and molecules tend to be in the lowest possible energy level. Physicists traditionally considered that to be the normal state of matter. Not all atoms are in the ground state because they always have some thermal energy above absolute zero. But at equilibrium the number of atoms in an energy level always decreases with the energy of the state, as shown in Figure 2-9. In fact, the decline can be steep.

Why does this make stimulated emission difficult? Because the best way to stimulate emission from an excited atom is with spontaneous emission from an identical excited atom. That would seem easy if you had a lot of atoms in the excited state, but in equilibrium more atoms would be in the low-energy state than in the excited state. In that case, spontaneous-emission photons would be more likely to encounter atoms in the lower state that would absorb them than atoms in the upper state that they could stimulate to emit another photon. So physicists were able to show that stimulated emission was possible in the 1920s, but they could not stimulate enough emission to be of any practical use.

For stimulated emission to dominate, the majority of atoms must be in an excited state, so spontaneously emitted photons are more likely to stimulate emission than to be absorbed by atoms in the ground state. This is called a population inversion, because the population is inverted from the normal situation in which more atoms are in lower levels than in higher levels. Stimulated emission can continue as long as the population inversion exists, but stops once the ground-state population becomes larger and photons are more likely to be absorbed than to stimulate emission.

Nobody knew how to produce a population inversion in the 1920s and 1930s. It seemed so counterintuitive that they called such a condition a "negative temperature" because in theory the only way to produce a population inversion was to have a temperature below absolute zero. Only after World War II did physicists realize they could produce a population inversion for more than a fleeting instant. You will learn more about that in Chapter 3.

2.3 INTERACTIONS OF LIGHT AND MATTER

So far, we have described light and its interaction with individual atoms. However, what is important in most laser applications is the interaction of light with bulk materials. That is the science of *optics*, and it depends on both the wavelength of light and the properties of the materials.

2.3.1 Optics and Materials

Light interacts with individual atoms and molecules in the air, but atoms are packed much closer together in liquids and solids. Visible wavelengths of 400 to 700 nm are more than a thousand times larger than an average atom (around 0.1 nm), so they interact with large numbers of atoms spread through the bulk material. Those interactions depend on both the wavelength and the composition of the material.

We usually sort objects into three classes according to how they interact with light:

1. Transparent objects (e.g., glass) transmit light
2. Opaque objects (e.g., dirt or rocks) absorb light
3. Reflective objects (e.g., mirrors) reflect light

However, nothing is perfectly transparent, opaque, or reflective. Thin slices of objects we consider opaque actually transmit some light. If you are reading a paper copy of this book, hold its pages together, and they are opaque, but hold a single page up to a bright light and some light will pass through. That is because absorption builds up quickly. If each page transmits 10% of the light striking it, 10 pages stacked together allow just 10^{-10} or one tenth of a billionth of the original light to get through. Likewise, geologists can see through rocks that look opaque by cutting them into slices so thin they transmit some light.

Everything reflects some light, whether we consider it transparent, opaque, or reflective. We see the light that objects reflect, and our eyes interpret the amount of reflection as dark or light. Sometimes our eyes can fool us. A full moon reflects only about 6% of the incident sunlight, but it looks bright when seen against a black night sky. White paint looks white because it reflects light uniformly across the visible spectrum. Green leaves look green because they reflect much more light in the green part of the spectrum than at other wavelengths. (Section 2.3.5 explains why mirrors reflect light differently than white paint.)

Transparent materials are important for optics, because light can pass through them. Nothing is perfectly transparent except for a perfect vacuum, which is, of course, really nothing. As Section 2.3.6 explains, light transmission depends on the wavelength. Glass is transparent through the visible spectrum, but it absorbs light in much of the infrared and ultraviolet. Ruby crystals and rose-colored glasses absorb blue, green, and yellow light but transmit red, so light emerging from them looks red to the eye. Finally, any transparent material also reflects some light at its surface; that is why you see reflections from indoors when you look out through a window at night.

Let us look a bit more at the details, starting with transparent materials.

2.3.2 Refractive Index

The most important property of a transparent material is its *refractive index*, n, which tells how fast light travels in the material relative to that in a vacuum. The velocity of light in a vacuum, denoted as c, is a universal constant, precisely defined as 299,792.458 kilometers per second, but often rounded to 300,000 km/sec or 186,000 miles/sec. Light slows down in matter, even something as tenuous as air. The refractive index measures how much longer light takes to pass through a solid by dividing the speed of light in air by the speed of light in the material:

$$n_{\text{material}} = \frac{c_{\text{vacuum}}}{c_{\text{material}}} \tag{2-9}$$

Because the speed of light is faster in a vacuum than in a material, the refractive index normally is greater than one. (Some very

Table 2-4. Refractive indexes of common materials for wavelengths near 500 nm, except where noted

Material	Index
Air (1 atmosphere)	1.000278 (usually approximated as 1.0003)
Water	1.33
Magnesium fluoride	1.39
Fused silica	1.46
Zinc crown glass	1.53
Crystal quartz	1.55
Optical glass	1.51–1.81*
Heavy flint glass	1.66
Sapphire	1.77
Zircon	2.1
Diamond	2.43
Silicon	3.49 @ 1.4 μm
Gallium arsenide	3.5 @ 1 μm

*Denotes depends on composition. Standard optical glasses have refractive indexes in this range.

interesting exceptions exist on the cutting edge of optical science, but they involve special materials with internal structures smaller than the wavelength of light, so you do not need to worry about them now.) Air is so tenuous that it has a very low refractive index of 1.000278 at atmospheric pressure, which is so small that it can be ignored for most optical systems.

It is important to note that the refractive index varies with wavelength. This must be considered in optical devices, particularly those built to transmit the whole visible spectrum, like binoculars. Table 2-4 lists the refractive indexes of some common materials near 500 nm, in the middle of the visible spectrum.

The frequency of light waves in solids is the same as in a vacuum, but the wavelength depends on the refractive index. Just as the refractive index slows the speed of light in a solid, it also decreases the wavelength, which equals the wavelength in vacuum divided by the material's refractive index n_{material}:

$$\lambda_{\text{material}} = \frac{\lambda_{\text{vacuum}}}{n_{\text{material}}} \tag{2-10}$$

2.3.3 Refraction

Light bends as it passes between two materials with different refractive index, such as from air into glass. This effect, shown in

Figure 2-11, is called *refraction* and depends on the refractive index. The closely spaced parallel lines in the figure represent the peaks of successive waves, one wavelength apart in the direction in which the light travels. In the low-index material at the top, the peaks are far apart, but the wavelength shrinks when the light slows down in the higher-index material at the bottom. The peaks stay in phase, so the change in refractive index bends the light in the direction shown. If the light wave passes into the same low-index material on the other side of high-index material, the light waves become longer, and the light bends back. You can see how if you turn the page upside down.

Refraction only occurs at the border between two transparent materials, not within the materials themselves. The amount of refraction is measured by comparing the direction of the light with the *normal angle,* which is perpendicular to the surface where refraction takes place, as shown in Figure 2-10. The angle is simple to calculate using Snell's law, which states that if light traveling in

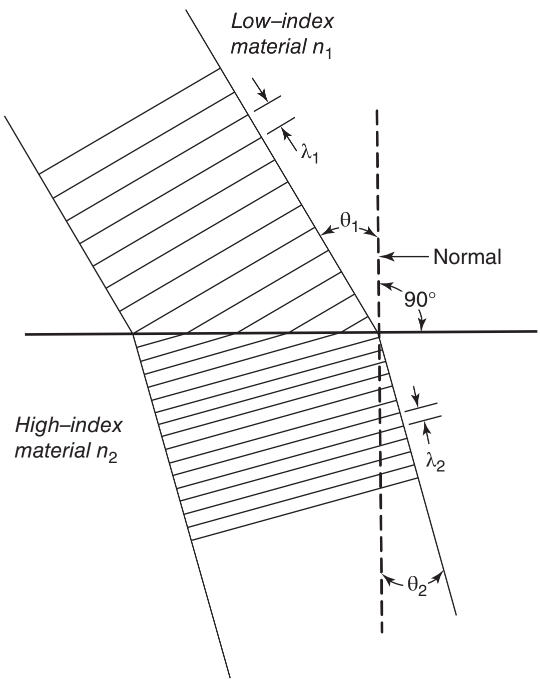

Figure 2-10. Refraction of light waves as they pass from a low-index medium (such as air) with refractive index n_1 to higher-index medium with index n_2.

a medium with refractive index n_1 strikes the surface of a material with index n_2 at an angle of θ_1 to the normal, the direction of light in the second material is given by θ_2:

$$n_1 \sin\theta_1 = n_2 \sin\theta_2 \tag{2-11}$$

You can also rewrite this to directly calculate the angle of refraction θ_2:

$$\theta_2 = \arcsin\left(\frac{n_1 \sin\theta_1}{n_2}\right) \tag{2-12}$$

where the arcsine is the inverse of the sine.

Suppose, for example, that light in water ($n_1 = 1.33$) strikes the surface of crystal quartz ($n_2 = 1.55$) at 30 degrees to the normal. The formula tells us that $\theta_2 = 25.4$ degrees, meaning that the light is bent closer to the normal. If the light were going in the other direction, it would be bent further from the normal. If the difference in refractive index were larger, as when going from air into quartz, the change in angle would be larger.

Something peculiar happens if light goes from a high-index material into a low-index material at a steep angle. Suppose, for example, that light in a quartz crystal hits the boundary with air ($n = 1.0003$) at a 50-degree angle to the normal. Plug the numbers into the equation above, and you find that θ_2 equals the arcsine (1.19). However, the sine of an angle cannot be greater than one, so your calculator will flag that as an error. If you try an experiment, you will find that the light does not escape into the air; it is all reflected back into the quartz, an effect called *total internal reflection* that makes diamonds sparkle and is the basis of light guiding in optical fibers.

2.3.4 Transparent and Translucent Materials

You may have been confused at some point by the distinction between transparent and translucent materials. Transparent materials are clear, like a window. Translucent materials transmit light, but are cloudy, like milk, wax paper, or ground glass. The difference is that transparent materials let light pass straight through, whereas translucent materials scatter the light rays, blurring them, so you cannot see clearly. This is similar to the difference