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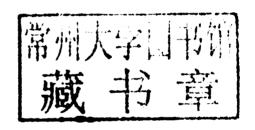




## **Introduction to Laser Technology**

**Fourth Edition** 

C. Breck Hitz
J. Ewing
Jeff Hecht





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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.

#### x Preface

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.

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# 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

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 <sup>1</sup>
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 <sup>2</sup>

Table 1.1. Some important commercial lasers

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.

#### WHAT ARE LASERS USED FOR? 1.1

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

<sup>&</sup>lt;sup>1</sup>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.

<sup>&</sup>lt;sup>2</sup>Excimers, like the glass lasers discussed in the note above, are pulsed lasers, capable of peak powers in the tens of megawatts.

<sup>\*</sup>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).

## 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,  $\lambda$ , 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  $\lambda$ .

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