1
Introduction

OVERVIEW A laser is a device that amplifies light and produces a highly directional, high-intensity beam that most often has a very pure frequency or wavelength. It comes in sizes ranging from approximately one tenth the diameter of a human hair to the size of a very large building, in powers ranging from 10^{-9} to 10^{20} W, and in wavelengths ranging from the microwave to the soft–X-ray spectral regions with corresponding frequencies from 10^{11} to 10^{17} Hz. Lasers have pulse energies as high as 10^4 J and pulse durations as short as 5×10^{-15} s. They can easily drill holes in the most durable of materials and can weld detached retinas within the human eye. They are a key component of some of our most modern communication systems and are the "phonograph needle" of our compact disc players. They perform heat treatment of high-strength materials, such as the pistons of our automobile engines, and provide a special surgical knife for many types of medical procedures. They act as target designators for military weapons and provide for the rapid check-out we have come to expect at the supermarket. What a remarkable range of characteristics for a device that is in only its fifth decade of existence!

INTRODUCTION

There is nothing magical about a laser. It can be thought of as just another type of light source. It certainly has many unique properties that make it a special light source, but these properties can be understood without knowledge of sophisticated mathematical techniques or complex ideas. It is the objective of this text to explain the operation of the laser in a simple, logical approach that builds from one concept to the next as the chapters evolve. The concepts, as they are developed, will be applied to all classes of laser materials, so that the reader will develop a sense of the broad field of lasers while still acquiring the capability to study, design, or simply understand a specific type of laser system in detail.

DEFINITION OF THE LASER

The word *laser* is an acronym for Light Amplification by Stimulated Emission of Radiation. The laser makes use of processes that increase or amplify light signals after those signals have been generated by other means. These processes include (1) stimulated emission, a natural effect that was deduced by considerations relating to thermodynamic equilibrium, and (2) optical feedback (present in most

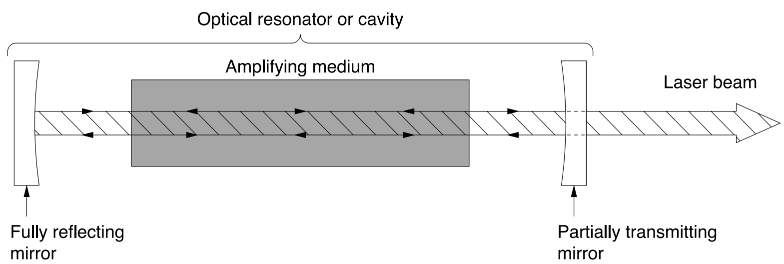

Figure 1-1 Simplified schematic of typical laser

lasers) that is usually provided by mirrors. Thus, in its simplest form, a laser consists of a gain or amplifying medium (where stimulated emission occurs), and a set of mirrors to feed the light back into the amplifier for continued growth of the developing beam, as seen in Figure 1-1.

SIMPLICITY OF A LASER

The simplicity of a laser can be understood by considering the light from a candle. Normally, a burning candle radiates light in all directions, and therefore illuminates various objects equally if they are equidistant from the candle. A laser takes light that would normally be emitted in all directions, such as from a candle, and concentrates that light into a single direction. Thus, if the light radiating in all directions from a candle were concentrated into a single beam of the diameter of the pupil of your eye (approximately 3 mm), and if you were standing a distance of 1 m from the candle, then the light intensity would be 1,000,000 times as bright as the light that you normally see radiating from the candle! That is essentially the underlying concept of the operation of a laser. However, a candle is not the kind of medium that produces amplification, and thus there are no candle lasers. It takes relatively special conditions within the laser medium for amplification to occur, but it is that capability of taking light that would normally radiate from a source in all directions – and concentrating that light into a beam traveling in a single direction – that is involved in making a laser. These special conditions, and the media within which they are produced, will be described in some detail in this book.

UNIQUE PROPERTIES OF A LASER

The beam of light generated by a typical laser can have many properties that are unique. When comparing laser properties to those of other light sources, it can be readily recognized that the values of various parameters for laser light either greatly exceed or are much more restrictive than the values for many common light sources. We never use lasers for street illumination, or for illumination within our houses. We don't use them for searchlights or flashlights or as headlights in our cars. Lasers generally have a narrower frequency distribution, or much higher intensity, or a much greater degree of collimation, or much shorter pulse duration, than that available from more common types of light sources. Therefore, we do use them in compact disc players, in supermarket check-out scanners, in surveying instruments, and in medical applications as a surgical knife or for welding detached retinas. We also use them in communications systems and in radar and military targeting applications, as well as many other areas. *A laser is a specialized light source that should be used only when its unique properties are required.*

THE LASER SPECTRUM AND WAVELENGTHS

A portion of the electromagnetic radiation spectrum is shown in Figure 1-2 for the region covered by currently existing lasers. Such lasers span the wavelength range from the far infrared part of the spectrum ($\lambda = 1{,}000\ \mu$m) to the soft–X-ray region ($\lambda = 3$ nm), thereby covering a range of wavelengths of almost six orders of magnitude. There are several types of units that are used to define laser wavelengths. These range from micrometers or microns (μm) in the infrared to nanometers (nm) and angstroms (Å) in the visible, ultraviolet (UV), vacuum ultraviolet (VUV), extreme ultraviolet (EUV or XUV), and soft–X-ray (SXR) spectral regions.

WAVELENGTH UNITS

$1\ \mu\text{m} = 10^{-6}$ m;
$1\ \text{Å} = 10^{-10}$ m;
$1\ \text{nm} = 10^{-9}$ m.

Consequently, 1 micron (μm) = 10,000 angstroms (Å) = 1,000 nanometers (nm). For example, green light has a wavelength of 5×10^{-7} m = 0.5 μm = 5,000 Å = 500 nm.

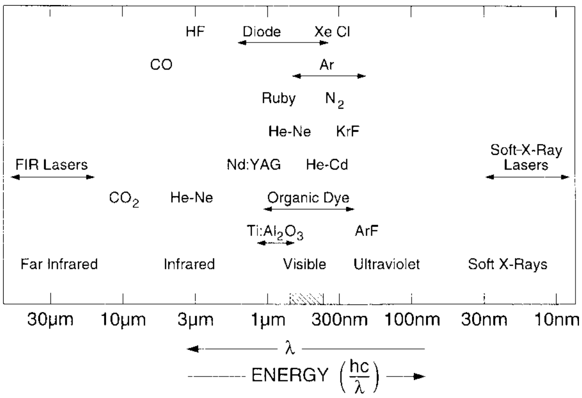

Figure 1-2 Wavelength range of various lasers

WAVELENGTH REGIONS

Far infrared: 10 to 1,000 μm;
middle infrared: 1 to 10 μm;
near infrared: 0.7 to 1 μm;
visible: 0.4 to 0.7 μm, or 400 to 700 nm;
ultraviolet: 0.2 to 0.4 μm, or 200 to 400 nm;
vacuum ultraviolet: 0.1 to 0.2 μm, or 100 to 200 nm;
extreme ultraviolet: 10 to 100 nm;
soft X-rays: 1 nm to approximately 20–30 nm (some overlap with EUV).

A BRIEF HISTORY OF THE LASER

Charles Townes took advantage of the stimulated emission process to construct a microwave amplifier, referred to as a *maser*. This device produced a coherent beam of microwaves to be used for communications. The first maser was produced in ammonia vapor with the inversion between two energy levels that produced gain at a wavelength of 1.25 cm. The wavelengths produced in the maser were comparable to the dimensions of the device, so extrapolation to the optical regime – where wavelengths were five orders of magnitude smaller – was not an obvious extension of that work.

In 1958, Townes and Schawlow published a paper concerning their ideas about extending the maser concept to optical frequencies. They developed the concept of an optical amplifier surrounded by an optical mirror resonant cavity to allow for growth of the beam. Townes and Schawlow each received a Nobel Prize for his work in this field.

In 1960, Theodore Maiman of Hughes Research Laboratories produced the first laser using a ruby crystal as the amplifier and a flashlamp as the energy source. The helical flashlamp surrounded a rod-shaped ruby crystal, and the optical cavity was formed by coating the flattened ends of the ruby rod with a highly reflecting material. An intense red beam was observed to emerge from the end of the rod when the flashlamp was fired!

The first gas laser was developed in 1961 by A. Javan, W. Bennett, and D. Harriott of Bell Laboratories, using a mixture of helium and neon gases. At the same laboratories, L. F. Johnson and K. Nassau demonstrated the first neodymium laser, which has since become one of the most reliable lasers available. This was followed in 1962 by the first semiconductor laser, demonstrated by R. Hall at the General Electric Research Laboratories. In 1963, C. K. N. Patel of Bell Laboratories discovered the infrared carbon dioxide laser, which is one of the most efficient and powerful lasers available today. Later that same year, E. Bell of Spectra Physics discovered the first ion laser, in mercury vapor. In 1964 W. Bridges of Hughes Research Laboratories discovered the argon ion laser, and in 1966 W. Silfvast, G. R. Fowles, and B. D. Hopkins produced the first blue helium–cadmium metal vapor laser. During that same year, P. P. Sorokin and J. R. Lankard of the IBM Research Laboratories developed the first liquid laser using an organic dye dissolved in a solvent, thereby leading to the category of broadly tunable lasers. Also at that time, W. Walter and co-workers at TRG reported the first copper vapor laser.

The first vacuum ultraviolet laser was reported to occur in molecular hydrogen by R. Hodgson of IBM and independently by R. Waynant et al. of the Naval Research Laboratories in 1970. The first of the well-known rare-gas–halide excimer lasers was observed in xenon fluoride by J. J. Ewing and C. Brau of the Avco–Everett Research Laboratory in 1975. In that same year, the first quantum-well laser was made in a gallium arsenide semiconductor by J. van der Ziel and co-workers at Bell Laboratories. In 1976, J. M. J. Madey and co-workers at Stanford University demonstrated the first free-electron laser amplifier operating in the infrared at the CO_2 laser wavelength. In 1979, Walling and co-workers at Allied Chemical Corporation obtained broadly tunable laser output from a solid-state laser material called alexandrite, and in 1985 the first soft–X-ray laser was successfully demonstrated in a highly ionized selenium plasma by D. Matthews and a large number of co-workers at the Lawrence Livermore Laboratories. In 1986, P. Moulton discovered the titanium sapphire laser. In 1991, M. Hasse and co-workers developed the first blue-green diode laser in ZnSe. In 1994, F. Capasso and co-workers developed the quantum cascade laser. In 1996, S. Nakamura developed the first blue diode laser in GaN-based materials.

In 1961, Fox and Li described the existence of resonant transverse modes in a laser cavity. That same year, Boyd and Gordon obtained solutions of the wave equation for confocal resonator modes. Unstable resonators were demonstrated in 1969 by Krupke and Sooy and were described theoretically by Siegman. *Q*-switching was first obtained by McClung and Hellwarth in 1962 and described later by Wagner and Lengyel. The first mode-locking was obtained by Hargrove, Fork, and Pollack in 1964. Since then, many special cavity arrangements, feedback schemes, and other devices have been developed to improve the control, operation, and reliability of lasers.

OVERVIEW OF THE BOOK

Isaac Newton described light as small bodies emitted from shining substances. This view was no doubt influenced by the fact that light appears to propagate in a straight line. Christian Huygens, on the other hand, described light as a wave motion in which a small source spreads out in all directions; most observed effects – including diffraction, reflection, and refraction – can be attributed to the expansion of primary waves and of secondary wavelets. The dual nature of light is still a useful concept, whereby the choice of particle or wave explanation depends upon the effect to be considered.

Section One of this book deals with the fundamental *wave* properties of light, including Maxwell's equations, the interaction of electromagnetic radiation with matter, absorption and dispersion, and coherence. Section Two deals with the fundamental *quantum* properties of light. Chapter 3 describes the concept of discrete energy levels in atomic laser species and also how the periodic table of the elements evolved. Chapter 4 deals with radiative transitions and emission linewidths and the probability of making transitions between energy levels. Chapter 5 considers energy levels of lasers in molecules, liquids, and solids – both dielectric solids and semiconductors. Chapter 6 then considers radiation in equilibrium and the concepts of absorption and stimulated emission of radiation. At this point the student has the basic tools to begin building a laser.

Section Three considers laser amplifiers. Chapter 7 describes the theoretical basis for producing population inversions and gain. Chapter 8 examines laser gain and operation above threshold, Chapter 9 describes how population inversions are produced, and Chapter 10 considers how sufficient amplification is achieved to make an intense laser beam. Section Four deals with laser resonators. Chapter 11 considers both longitudinal and transverse modes within a laser cavity, and Chapter 12 investigates the properties of stable resonators and Gaussian beams. Chapter 13 considers a variety of special laser cavities and effects, including unstable resonators, Q-switching, mode-locking, pulse narrowing, ring lasers, and spectral narrowing.

Section Five covers specific laser systems. Chapter 14 describes eleven of the most well-known gas and plasma laser systems. Chapter 15 considers twelve well-known dye lasers and solid-state lasers, including both dielectric solid-state lasers and semiconductor lasers. The book concludes with Section Six (Chapter 16), which provides a brief overview of frequency muliplication with lasers and other nonlinear effects.

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SECTION ONE

FUNDAMENTAL WAVE PROPERTIES OF LIGHT

2

Wave Nature of Light

The Interaction of Light with Materials

OVERVIEW This chapter will consider some of the wave properties of light that are relevant to the understanding of lasers. We will first briefly review the derivation of Maxwell's wave equations based upon the experimentally obtained laws of electricity and magnetism. We will consider Maxwell's equations in a vacuum, and will demonstrate the equivalence of light and electromagnetic radiation. We will describe both the phase velocity and group velocity of light and will show how polarized light occurs in these transverse electromagnetic waves.

We will then use the wave equations to consider the interaction of electromagnetic waves with transparent and semitransparent materials such as those used for the gain media of solid-state lasers. We will derive expressions for the optical constants η and κ (the real and imaginary components of the index of refraction) that suggest the presence of strong absorptive and dispersive regions at particular resonant wavelengths or frequencies of the dielectric materials. These are regions where η and κ vary quite significantly with frequency. These resonances will later (in Chapters 4, 5, and 6) be related to optical transitions (both emission and absorption) between energy levels in those materials. We will conclude the chapter with a brief description of coherence.

2.1 MAXWELL'S EQUATIONS

Maxwell's wave equations, predicting the propagation – even in a vacuum – of transversely oscillating electromagnetic waves, were the first indication of the true nature of light. His wave equations, published in 1864, predicted a velocity c for such a wave in a vacuum ($c = (\mu_0 \varepsilon_0)^{-1/2}$) that agreed with independent measurements of the velocity of light. This velocity was based solely upon the value of two previously known constants: μ_0, the permeability of the vacuum; and ε_0, the permittivity of the vacuum. These constants had arisen from totally separate investigations of electricity and magnetism that had nothing to do with studies of light! By definition, the exact value of μ_0 is $4\pi \times 10^{-7}$ H/m; the measured value of ε_0 is 8.854×10^{-12} F/m.

The fundamental electric and magnetic field vectors **E** and **B** (respectively) can produce forces on physical entities. These vectors are measurable quantities that led to the experimentally derived laws of Gauss, Biot–Savart, Ampere, and Faraday, all of which are briefly outlined in what follows. These laws in turn formed the foundation upon which Maxwell built to develop his equations predicting the existence and properties of electromagnetic radiation.

In addition to **E** and **B**, we must consider properties associated with the electromagnetic state of matter. Such matter can be described at a given location in space by four quantities:

(1) the charge density ρ (charge per unit volume);
(2) the polarization **P** (electric dipole moment per unit volume) for magnetic materials, in particular for a dielectric material;
(3) the magnetization **M** (magnetic dipole moment per unit volume); and
(4) the current density **J** (current per unit area).

For our purposes, all of these quantities are assumed to be average values.

Other relationships that will be useful include:

(5) the Lorentz force law,

$$\mathbf{F} = q(\mathbf{v} \times \mathbf{B}), \tag{2.1}$$

where **F** is the force resulting from a charge q moving with a velocity **v**; and
(6) a form of Ohm's law given by

$$\mathbf{J} = \sigma \mathbf{E}, \tag{2.2}$$

which describes the response of electrons in a conducting medium of conductivity σ to an electric field vector **E**.

Maxwell defined the electric displacement vector **D** as follows:

$$\mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P} \quad \text{(for general use)}; \tag{2.3}$$

D is used so as to avoid explicit inclusion of the charge associated with the polarization **P** in Gauss's flux law.

For the case of free space,

$$\mathbf{D} = \varepsilon_0 \mathbf{E}, \tag{2.4}$$

and for an isotropic linear dielectric,

$$\mathbf{D} = \varepsilon \mathbf{E}, \tag{2.5}$$

which describes the aggregate response of the bound charges to the electric field.

An alternate way of expressing this is to write

$$\mathbf{P} = (\varepsilon - \varepsilon_0)\mathbf{E} = \chi \varepsilon_0 \mathbf{E}, \tag{2.6}$$

which gives the relationship between the polarization **P** and the electric field **E** that produces **P**. The factor χ, known as the *electric susceptibility,* is given by

$$\chi = (\varepsilon/\varepsilon_0) - 1; \tag{2.7}$$

χ is a useful parameter when considering effects in the optical frequency range. For spherically symmetric materials such as glass, χ is a simple scalar quantity,