Chapter 1

An Introduction to Lasers

The word **LASER** is an acronym for **L**ight **A**mplification by **S**timulated **E**mission of **R**adiation. The name indicates that the process of stimulated emission makes a laser work. Stimulated emission is studied in detail in this book. The name does not describe the special characteristics of laser light that makes lasers so useful. Compared to conventional sources of light such as an incandescent light, the light from a laser may be quite intense, very monochromatic, and may be emitted in a beam with an angular divergence limited by diffraction. The monochromaticity and high degree of collimation of a laser beam are manifestations of the coherence of the laser beam. If one repeatedly samples the electromagnetic field in a light beam at different points in space either longitudinally along the beam axis or transversely across the beam axis and finds that definite phase differences are maintained, then the light is said to be coherent. These properties imply that laser light is nearly a perfect classical sinusoidal electromagnetic wave.

Lasers have many applications in scientific or engineering research, in telecommunications, in industry, and in medicine. For example in scientific or engineering research variable wavelength lasers are used for spectroscopy experiments, for the ultra-sensitive detection of atoms or molecules, for atom trapping experiments, for laser isotope separation experiments, for measurements of the time dependence of physical or chemical reactions, for studies of laser induced chemical reactions, and for many other research projects. In commercial or industrial applications lasers are used for the transmission of communication signals, for reading bar codes, for cutting of precise patterns in metal tooling, and for many other operations. In medicine lasers are used for the treatment of detached retinas, for sculpting corneas, for the treatment of ulcers, for use as a precision scalpel, and for many other applications. The remarkable properties of lasers are the result of stimulated emission. This book discusses how stimulated emission is utilized to produce laser action, and how a number of lasers operate. Because the applications of lasers is so enormous no effort is made to discuss the applications of lasers. The purpose of Chapter 1 is to introduce the concepts and notation used in this book, to provide a brief review of the theories of electricity and magnetism and atomic physics, that are involved in the operation of lasers, and to describe the basics of how a laser works.

1.1 Electromagnetic Waves

Light is an electromagnetic wave. The light generated by a laser must satisfy Maxwell's equations just as any electromagnetic wave does. Maxwell's equations are

$$\begin{aligned} \nabla \cdot \boldsymbol{D} &= \rho \\ \nabla \cdot \boldsymbol{B} &= 0 \\ \nabla \times \boldsymbol{E} &= -\frac{\partial \boldsymbol{B}}{\partial t} \\ \nabla \times \boldsymbol{H} &= j + \frac{\partial \boldsymbol{D}}{\partial t} \end{aligned} \tag{1.1}$$

where $\boldsymbol{D}$, $\boldsymbol{E}$, $\boldsymbol{B}$, and $\boldsymbol{H}$ are the displacement, the electric field, the magnetic field, and the magnetic intensity vectors respectively. The charge density is ρ and the current density is j. An electromagnetic wave consists of orthogonal electric and magnetic fields. For many purposes, the light from a laser can be described as an ideal plane wave. The electric field in a plane wave propagating in a vacuum in the direction of the wave vector $\boldsymbol{k}$ can be represented by

$$\boldsymbol{E} = \boldsymbol{E}_0 \; e^{i(\boldsymbol{k}\cdot\boldsymbol{r} - \omega t + \phi)} \tag{1.2}$$

where $k = 2\pi/\lambda$ is the magnitude of the wave vector, λ is the wavelength of the light, $\nu = c/\lambda$ is the frequency of the electromagnetic wave, c is the speed of light in a vacuum, $\omega = 2\pi\nu$ is the angular frequency, $\boldsymbol{r}$ is the position, t is the time, and ϕ is the phase constant. The complex notation is convenient for describing the field of an electromagnetic wave. The actual electric field is obtained by taking the real part of the expression in Equation 1.1. The vector $\boldsymbol{E}_0$ is orthogonal to the vector $\boldsymbol{k}$. In the International System of units (SI) the electric field, $\boldsymbol{E}$, has units of Volts per meter (V/m). The magnetic field associated with this plane electromagnetic wave is given by

$$\boldsymbol{B} = \boldsymbol{B}_0 \; e^{i(\boldsymbol{k}\cdot\boldsymbol{r} - \omega t + \phi)} \tag{1.3}$$

The magnetic field, $\boldsymbol{B}$, has units of Tesla (T) or Webers per square meter (W/m^2). The vector $\boldsymbol{B}_0$ is orthogonal to both the vectors $\boldsymbol{E}_0$ and $\boldsymbol{k}$. Maxwell's equations require that $B_0 = E_0/c$ (in SI units) where B_0 and E_0 are the magnitudes of $\boldsymbol{B}_0$ and $\boldsymbol{E}_0$ respectively. If an electromagnetic wave with frequency ν is propagating in a medium with an index of refraction, n, then the speed of light in the medium (i.e. the phase velocity of the wave) is given by $v = c/n$, and in the expression for the electromagnetic fields one should replace c with v. The index of refraction of the medium is a function of the frequency of the electromagnetic wave. The frequency of an electromagnetic wave in a medium with index n is the same as in vacuum, and the wavelength in a medium is equal to the wavelength in vacuum divided by the index of refraction of the medium. The electric and magnetic fields of an electromagnetic wave are orthogonal, and the vector product of the electric and magnetic fields, $\boldsymbol{E}_0 \times \boldsymbol{B}_0$, is in the direction of the propagation of the electromagnetic wave, i.e. in the direction of $\boldsymbol{k}$. The relation between the speed of light in a medium, the wave vector, and the frequency of the wave is $v = c/n = \lambda\nu = \omega/k$. Lasers with wavelengths in the infrared, visible, ultraviolet and even the X-ray regions of the electromagnetic spectrum have been constructed. Because the light generated by a laser satisfies Maxwell's equations, just as any electromagnetic wave must, laser beams obey the ordinary laws of optics including the laws for reflection, refraction, and diffraction.

The light generated by a laser may be very coherent. A light beam is *coherent* if there a fixed relationship between the phase at different locations of the beam. The coherence of the laser light is due to its generation by stimulated emission. Laser beams can have large longitudinal coherence lengths. The *longitudinal* coherence length is the distance parallel to the direction of propagation, over which the laser light wave maintains its coherence. This is often expressed as a *coherence time* where the coherence time is equal to the longitudinal coherence length divided by the velocity of propagation of the wave. Laser beams can also have large transverse coherence lengths. The *transverse* coherence length is the distance orthogonal to the direction of propagation over which the laser beam is coherent. The coherence time, the longitudinal coherence length, and the bandwidth of the laser are all simply related. The bandwidth of a laser is the spread in frequencies in the laser light. For example if the laser operates on average for 10^{-3} s without a phase slip or disruption, then the coherence time is 10^{-3} s and the longitudinal coherence length is $(10^{-3}c) = 3\times10^5$ m. A Michelson interferometer with a path difference up to 3×10^5 m will produce sharp fringes using the laser as a light source. The relationship of the coherence time of the laser to the laser bandwidth is analyzed carefully in a Chapter 7 of this book where it is shown that the laser bandwidth is given by the inverse of π times the coherence time. Thus a beat wave experiment with a stable source shows that a laser with a coherence time of 10^{-3} s has a bandwidth of $(\pi 10^{-3})^{-1}\ \mathrm{s}^{-1} = 318\ \ \mathrm{Hz}$.

In later chapters it is shown that the light emitted by a laser can be diffraction limited so that the light can emerge into a small solid angle. This means that a laser beam can be very bright i.e. it can have a large value of the power per solid angle. A laser beam can be focused into a very small diffraction limited spot. At the focus the laser beam can have an extremely high intensity i.e. a high power per area.

1.2 Photons

In Section 1.1 we briefly reviewed the wave properties of light. The wave character of light is shown by interference or diffraction experiments. Light also may be thought of as consisting of packets of energy or particles called photons. The photon behavior of light arises because of the quantization of the electromagnetic field. Each photon with frequency ν carries an energy given by $h\nu = \hbar\omega$ where $h = 6.626 \times 10^{-34}$ J s is Planck's constant, and where $\hbar = h/2\pi$. The quantum or particle character of light is apparent in experiments such as the Compton scattering of photons. The energy density, w, in an electromagnetic wave is given by the expression

$$w = \frac{\epsilon\, \boldsymbol{E}_{\mathrm{RMS}}^2}{2} + \frac{\boldsymbol{B}_{\mathrm{RMS}}^2}{2\mu_0} \tag{1.4}$$

where $\boldsymbol{E}_{\mathrm{RMS}}$ and $\boldsymbol{B}_{\mathrm{RMS}}$ are the root mean square values of the fields, $\epsilon = K\epsilon_0$ is the electric permitivity of the material in which the wave is traveling, $\epsilon_0 = 8.854 \times 10^{-12}\ \mathrm{C^2N^{-1}m^{-2}}$ is the permitivity of free space, K is the dielectric constant of the material at the frequency ν, and $\mu_0 = 4\pi \times 10^{-7}\ \mathrm{TA^{-1}m}$ is the permeability of free space. In Eq. 1.4 it is assumed that the relative permeability of the material is one, i.e., that the magnetic susceptibility is zero. The dielectric constant and the index of refraction are related by $K = n^2$. Since the energy of a photon is quantized it follows that the energy density in an electromagnetic wave with a given frequency and wave vector is also given by

$$w = n_{\mathrm{ph}}\, h\nu \tag{1.5}$$

where n_{ph} is the density[1] of photons with a given frequency and wave vector in the electromagnetic field. Only photons with particular allowed frequencies and wave vectors can exist in an optical cavity as is discussed in later chapters. A photon with one of the given allowed frequencies and wave vectors is said to be in one of the allowed modes of the cavity. Thus n_{ph} is the photon density in a mode with the particular frequency and wave vector. The intensity, I_ν , of a light beam with a given frequency and wave vector is given by

$$I_\nu = \frac{wc}{n} = \frac{n_{\mathrm{ph}}\, h\nu c}{n} \tag{1.6}$$

where I is measured in Watts per square meter (W/m^2). In discussing lasers it is more convenient to treat some problems using the wave picture whereas it is more convenient to treat other problems using the particle or photon picture. In many situations it is convienent to think of a photon as a wave packet that has a length equal to the longitudinal coherence length and a transverse size equal to the transverse coherence length.

1.3 Spontaneous and Stimulated Emission

Atoms and molecules have quantized energy levels. It is found experimentally that isolated atoms (or molecules) in an excited level, labeled u, can decay radiatively to a lower level, labeled l, with the emission of a photon. The radiative decay of an isolated atom is called spontaneous emission. The frequency of the photon emitted in spontaneous decay is related to the energy difference between the atomic energy levels by

$$\nu_0 = \frac{\Delta W}{h} = \frac{W_u - W_l}{h} \tag{1.7}$$

where W_u is the energy of the upper level u and W_l is the energy of the lower level l. It is found experimentally that when an ensemble of atoms in an excited level, such as level u, decays radiatively by spontaneous emission the number density of atoms in the upper level decreases exponentially with time provided that there is no source of production of atoms into the upper level. It is also found experimentally that an atom can absorb a photon from the electromagnetic field. The absorption of a photon with frequency ν_0 excites an atom initially in lower level l into the upper level u. It might be thought that absorption and spontaneous emission are adequate

[1]The number *density* of photons is the number of photons per unit volume per unit frequency. In general this text uses the term density to mean number density for atoms, molecules, photons and modes in the electromagnetic field.

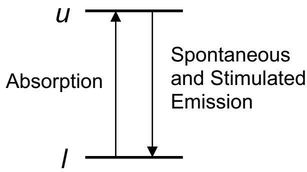

Fig. 1.1 Two atomic energy levels with absorption and spontaneous and stimulated emission indicated.

to explain the level populations of atoms exposed to radiation fields. This is, however, not the case. A third process called stimulated emission is necessary. Stimulated emission occurs when a photon interacts with an atom in an excited level, and the atom decays to a lower level with the emission of a second photon. Figure 1.1 shows two atomic energy levels with absorption and spontaneous and stimulated emission occurring. In stimulated emission the photon that is emitted is identical in every way with the photon that causes the stimulated emission so that the photon that is emitted has the same frequency, the same phase, the same polarization, and the same direction of propagation as the original photon. Einstein analyzed the level populations of atoms in the presence of electromagnetic radiation, and he demonstrated the necessity for considering absorption, spontaneous emission, and stimulated emission in determining the level populations of atoms exposed to radiation fields.

Stimulated emission is the subject of much of this text book, so that here we present only a brief discussion as to why stimulated emission is necessary. In order to understand this consider a simple physical system composed of an ensemble of atoms that is maintained in thermal equilibrium with a container at the temperature T. The atoms are therefore exposed to blackbody radiation characteristic of the temperature T. That segment of the blackbody spectrum at frequencies corresponding to the energy differences between different levels of the atoms can be absorbed by the atoms. Atoms in excited levels decay both by spontaneous and induced emission. In order to see that induced emission is necessary, consider the situation that would arise if there were no stimulated emission. In this case, the population of any excited level would be, in the steady state, determined by equating the rate at which the excited atoms are produced by absorption, to the rate at which the excited atoms decay by spontaneous emission. The number of blackbody photons per unit frequency and unit volume increases monotonically with increasing temperature, and hence the absorption rate per atom increases monotonically with the temperature. The spontaneous decay rate per excited atom is independent of the temperature. When the temperature is large enough that the absorption rate per atom exceeds the spontaneous decay rate per atom the population in an upper level would exceed the population in a lower level if there were no mechanism other than spontaneous emission for the decay of atoms in the upper level to the lower level. This is, however, not physically reasonable because in thermal equilibrium the populations of the various energy levels in an atom must be given by the Boltzmann distribution, which predicts that the lower level must have a higher population than the upper level. Therefore some process leading to the depopulation of the upper level other than spontaneous emission must occur. That process is the stimulated emission of radiation. When one calculates the populations of atomic levels by equating the absorption rate per atom into the upper level with the sum of the decay rates per atom due to spontaneous emission plus stimulated emission one finds that the population of the atomic levels satisfies the expected Boltzmann distribution. The qualitative discussion presented in this section is put on a quantitative basis in Chapter 2 where the process of stimulated emission is analyzed in detail and in Chapter 3 where stimulated emission is shown to lead to laser action.

One final comment on stimulated emission may be appropriate here. Although our discussion has focused on transitions in atoms where the energy levels are quantized, any process that radiates spontaneously can be stimulated to radiate. Stimulated emission is not an intrinsically quantum mechanical effect, and classical systems that radiate can be stimulated to radiate. The free electron laser is an example of a classical system that utilizes the stimulated emission of radiation.

1.4 Lasers

The concept of a laser was proposed by Schawlow and Townes. A typical laser is indicated schematically in Figure 1.2. It is made up of an active "lasing" medium and an *optical cavity.* Chapter 7 describes the requirements of the optical cavity and various designs used in some lasers. Some properties of the lasing medium are addressed in Chapters 5 and 6, along with complete laser systems in Chapters 8-9.

Although a substantial part of this book is devoted to the discussion of particular lasers a short discussion of some particular lasers may be in order here as an introduction. The most important lasers are the solid state

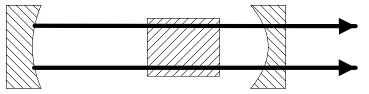

Fig. 1.2 A schematic diagram of a laser.

lasers. Solid state lasers are very reliable and some can be tuned to a particular wavelength and some can produce very high output power. A common type of solid state laser is the semiconductor diode laser, for instance a GaAlAs-GaAs-GaAlAs sandwich that lases in the near infrared region of the spectrum and widely used for optical data storage (CD-ROM). Semiconductor lasers are also used extensively for communications, for readout of bar codes, and for numerous other applications. Semiconductor lasers also have extensive uses in scientific research where they are used as narrow band width lasers for absorption spectroscopy and for many other scientific purposes. These lasers can operate continuously. This is called cw (continuous wave) operation. Semiconductor lasers usually are operated at low output powers, but some can be operated with very high output powers. The intensity of semiconductor lasers can be very rapidly changed as a function of the time. This is called modulation of the laser intensity and is used in high-speed optical communication. Glass or silica fiber lasers are often used to amplify the signals from diode lasers.

A type of cw gas discharge laser is the helium-neon (He-Ne) laser. This gas discharge laser operates with a wave length of 632.8 nm and with typical output powers of a few mW. The HeNe laser is sometimes used for college demonstrations. The Ar ion laser is also a gas discharge laser. The Ar ion laser can have an optical output power in the visible of 10's of Watts. Another gas discharge laser is the CO_2 laser, which operates in the infra-red with a wavelength of 10.6 microns (μm) and can have high output power levels. An application of the CO_2 laser is for machine tooling. Gas lasers are not used as often as they were in the past due primarily to their short lifetimes and lack of reliability. The operating wavelengths of various lasers are shown in Figure 1.3.

Some lasers are typically operated in a pulsed mode rather than cw.

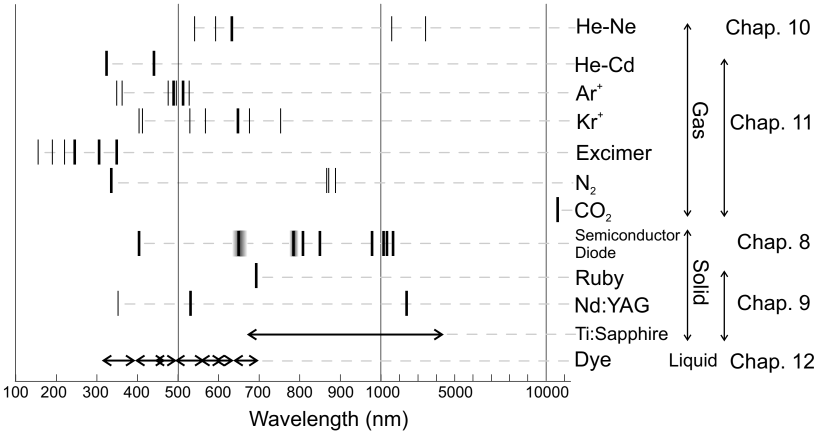

Fig. 1.3 Wavelengths of some common lasers.

These lasers can operate with instantaneous peak powers that are very high. Lasers that can operate in a pulsed mode include Nd:YAG lasers, Nd:Glass lasers, titanium-sapphire (Ti:Sapph) lasers, and excimer lasers. Common uses for these lasers are for the pumping of high power pulsed tunable lasers or for other applications such as irradiating the photo resist material in the manufacture of semiconductor chips.

All lasers are tunable over some spread in wavelength. For many lasers the range over which the laser can be tuned is, however, very small and these lasers are called fixed frequency lasers. An example of a fixed frequency laser is a HeNe laser. For other lasers the operating wavelength can be varied over a substantial range, sometimes hundreds of nanometers. These lasers are called tunable lasers. Tunable lasers are used for application where it is desireable to set the laser to a particular desired wavelength such as scientific applications like spectroscopy and other applications. Titanium-sapphire lasers, diode lasers, and free electron lasers are examples of tunable lasers. One often hears the statement "Lasers can be very powerful." While this statement is true it requires some explanation. Even a powerful cw laser such as the Ar ion laser which has an output optical power of 15 W emits only a few times as much optical power as a 100 W incandescent light bulb. It should be noted that a 100 W incandescent light uses 100 W of power from the electric power grid but only about 3-6% of that power or about 3-6 W is converted into visible photons. Of course the Ar ion laser has a much higher brightness than the incandescent light since the Ar ion laser emits photons into a very small solid angle whereas the incandescent light emits photons into all directions. In a pulsed laser, one can talk about both the average power and the peak power. Some pulsed lasers may have a low average power (i.e., by having a long delay 'off' period between pulses), but extremely high peak power. Indeed, by limiting the 'on' period to a very short pulse duration one can produce very high optical powers even if the energy per pulse is relatively modest. Consider a pulsed Nd:YAG laser which produces a string of light pulses with an energy per pulse of $E = 0.1$ J in optical radiation and with a pulse duration of $t = 10^{-8}$ s. The peak power of this laser is about $P_\mathrm{p} = E/t = 10^7$ W. If the Nd:YAG laser operates with a repetition rate of 20 Hz then the laser has an average output of power of $P_\mathrm{av} = 20E = 2$ W. In this example the ratio of the peak output power and the average output power is $P_\mathrm{p}/P_\mathrm{av} = 5\times10^6$. This is rather typical. Pulsed lasers can have very high peak output powers but usually have moderate to low average output powers; cw lasers typically have moderate to low output powers. There are only few lasers such as the CO_2 laser that can operate with cw output powers of 1 kW or more.

This book discusses how a number of different lasers operate in detail, but only briefly touches on a few scientific or engineering applications since the variety of applications is simply too vast to cover adequately. The discussion in this chapter is intended only to introduce the reader to the many types of lasers and to familarize the reader with the notation used in this text.

Summary of Key Ideas

- Light is emitted from transitions between the quantized energy levels of atoms and molecules, $\Delta W = W_u - W_l = h\,\nu = hc/\lambda$.
- Excited levels of atoms or molecules decay by either spontaneous or stimulated emission.
- Lasers utilize stimulated emission to produce coherent light beams.
- Lasers come in many varieties: pulsed or cw, operating with a fixed wavelength or tunable over a range of wavelengths (Fig. 1.3), and utilize a number of different mediums (gas discharges, solid crystals, *etc.*..).

Suggested Additional Reading

Charles H. Townes, *How the Laser Came to Happen: Adventures of a Scientist*, Oxford University Press (2002).

William T. Silfvast, *Laser Fundamentals*, Cambridge University Press (1996).

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Problems

1. An electromagnetic wave is traveling in a vacuum in the direction from $-x$ toward $+x$. The amplitude of the electric field in the wave is 0.1 V/m and the frequency of the wave is 5×10^{14} Hz. The wave is polarized along the y axis i.e. the electric field lies parallel or anti parallel to the y axis. (a) What is the wavelength? (b) Write an expression for the electric field of the electromagnetic wave if the electric field is zero at $x = 0$ and $t = 0$. (c) What is the magnitude and direction of the wave vector of the electromagnetic wave? (d) What is the magnitude and direction of the magnetic field in the electromagnetic wave?

2. An electromagnetic wave traveling in free space with $\lambda = 500$ nm has a coherence time of 5×10^{-4} s. (a) What is the longitudinal coherence length? Express your answer in terms of both meters and wavelengths. (b) What is the bandwidth of the laser?

3. A photon traveling in free space has a wavelength of 500 nm. What is the energy of the photon? Give your answer both in joules and in electron volts.

4. Show that a photon with a wavelength λ in nanometers has an energy, E, in electron volts of $E = 1239.85/\lambda$. (It will be useful to remember this relationship.)

5. A single mode electromagnetic wave in a vacuum is 1 cm in diameter, has a wavelength of 500 nm, and an intensity of 0.1 W/m^2. (a) What is the energy density in the wave? (b) What is the electric field in the wave? (c) What is the magnetic field in the wave? (d) What is the photon density in the wave?

6. If the light beam described in Problem 5 is focused to a spot 100 microns in diameter what are the intensity, the energy density, and the electric field at the focus?

7. An atom has an upper energy level 2.1 eV above the ground level. If the atom spontaneously makes a transition from the upper level to the ground level what is the wavelength and frequency of the emitted radiation?

8. If an electromagnetic wave with wavelength $\lambda = 500$ nm in vacuum passes from a vacuum into a material with an index of refraction $n = 1.5$, what are the wavelength and frequency inside the material?

9. A pulsed laser has a repetition rate of 20 pulses per second and an average power of 10 mW. If each pulse is 5 nsec in duration what is the peak instantaneous power emitted during a pulse?

10. For the laser of Problem 9 is the coherence time necessarily 5 nsec? Explain your answer.