1. A Brief History

As with most scientific fields, it is very difficult to say, "On this day the idea of a laser was conceived." Roots of the laser concept lie as far back as 1940, when Valentin A. Fabrikant speculated on the possibility of "molecular amplification" in his doctoral thesis. However, it is traditional to place the origin of the maser and laser in the late 1940s. A number of excellent reviews of the history of this era have been published and only the major points are summarized here.

For a variety of reasons, it is easier to obtain amplification of electromagnetic waves in the microwave spectrum. Thus, the first devices to demonstrate gain (see the Appendix for definitions of common laser terms and Section 2.2 for more information on gain) by *stimulated emission* (see Section 1.4) were microwave devices termed masers (Microwave Amplification by the Stimulated Emission of Radiation).

The idea of using stimulated emission as a means of amplifying electromagnetic radiation in the microwave spectrum seems to have been independently conceived of by Charles H. Townes at Columbia University, Joseph Weber at the University of Maryland, and Alexander M. Prokhorov and Nikolai G. Basov at the Lebedev Physics Institute (Moscow). The first maser (a 24-GHz ammonia device) was operated by James P. Gordon, Townes, and Herbert J. Zeiger at Columbia in 1954.

The successful operation of the ammonia maser immediately generated discussion as to whether these principles could be applied to visible wavelengths. At the time, there were a number of issues that suggested that it would be quite difficult to construct a visible maser. The three major issues were: 1) increased pumping requirements as the wavelength decreases, 2) creating a single mode cavity (as is traditional for masers) at visible wavelengths, and 3) locating materials possessing visible transitions with a sufficiently high quantum efficiency (see Section 2.1).

In 1951, Fabrikant filed a patent entitled "A method for the amplification of electromagnetic radiation (ultraviolet, visible, infrared and radio) distinguished by the fact that the amplified radiation is passed through a medium which, by means of auxiliary radiation of other means, generates excess concentrations, in comparison with the equilibrium concentration of atoms, other particles, or systems at upper energy states corresponding to the excited states." The patent was filed on June 18, 1951, but not granted until 1959. For a variety of reasons, this patent had little impact on either the Soviet Union or the international development of lasers.

In 1954, Robert H. Dicke developed the idea of using a short excitation pulse to produce a population inversion (see Section 1.4). This inversion would then generate an intense burst of amplified spontaneous emission. This idea plus the idea of using a Fabry-Perot etalon (see Section 3.2) as a resonant cavity (see Chapter 4) appear

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in his 1958 patent entitled "Molecular Amplification and Generation Systems and Methods." In 1957, Gordon Gould conceived of the idea of using a Fabry-Perot cavity as part of a laser structure. He documented his ideas in his laboratory notebook under the title of "laser" (Light Amplification by Stimulated Emission of Radiation). He had his notebook notarized on November 13, 1957, by a candy-store clerk. Gould then attempted to acquire a patent on these ideas. After a great deal of legal fuss, he obtained four patents: one in 1977 on optically pumped laser amplifiers, one in 1979 on a broad range of laser applications, one in 1987 on electrical discharge pumped lasers, and one in 1988 on Brewster angle windows for lasers. Many U.S. laser companies still pay royalties under license agreements on these patents.

In 1958, Schawlow and Townes wrote a seminal paper entitled "Infrared and Optical Masers," discussing the various aspects of constructing an optical maser. In this paper a number of questions regarding the practicality of lasers were discussed. The required pumping power was calculated (10 mW for a 1-cm cube) and shown to be practical, the question of using a multimode cavity was discussed, and a number of schemes for mode selection (including a long cavity Fabry-Perot) were presented. The possibility for three and four-state (see Section 2.1) solid-state lasers, linewidth (see Section 2.1), and tunability (see Chapter 11) were also briefly mentioned.

The appearance of this paper caused a great deal of interest in the scientific community. A number of laser programs were initiated, mostly distinguished by the choice of the laser material. Peter P. Sorokin and Mirek Stevenson at IBM focused on calcium fluoride doped with a rare earth, Theodore Maiman at Hughes pursued ruby, and Ali Javan at Bell Laboratories worked with a helium-neon mixture. (Ruby as a laser material is discussed in Section 11.3 and helium-neon as a laser material is discussed in Section 9.1.)

On May 16, 1960, Maiman and his coworkers achieved laser action in a "pink" (low chromium concentration) ruby rod. Maiman submitted his paper to Physical Review Letters, where it was rejected. Maiman then sent a paper to Nature and arranged a press conference to discuss the development. The result was received with skepticism, because in Schawlow's paper, ruby had been rejected as a laser material due to a presumed low quantum efficiency.

As a result of the Hughes publicity, a group from Bell Laboratories reproduced Maiman's results and submitted a paper to Physical Review Letters. This paper was accepted and published on October 1, 1960. Soon after, the Bell Laboratories group published another paper reporting laser action in "red" ruby.

This flurry of Physical Review Letter papers from the Bell Laboratories group caused much confusion as to who was responsible for the first demonstration of laser action. Many scientists assumed that the Bell Laboratories group had obtained laser action prior to Maiman at Hughes. Although Maiman published in Physical Review somewhat later, uncertainty remained for several years.

The majority of early laser schemes were complex. Maiman's demonstration of laser action in a simple and elegant experiment dramatically altered the direction of laser development. Soon after Maiman's demonstration of laser action in ruby, Sorokin and Stevenson of IBM switched to a flashlamp pumped rod design for their uranium-doped calcium fluoride laser. This laser lased on its first try in November 1960. A few weeks later, Sorokin and Stevenson obtained laser action in samarium-doped calcium fluoride. Although doped calcium fluoride is not a commonly used laser material today, these experiments were the first demonstrations of laser action in a four-state material.

The floodgates were now open to laser development. In rapid succession, a host of new materials were found to lase. On December 12, 1960, Ali Javan, William R. Bennett, Jr., and Donald Herriott obtained laser action in a helium-neon gas mixture. In 1963, C. Kumar Patel obtained laser action in carbon dioxide. In 1964, Joseph Geusic, H. M. Marcos, and Le Grand Van Uitert obtained laser action in Nd:YAG, and William Bridges obtained laser action in argon-ion. (Carbon dioxide lasers are discussed in Section 12.1. Nd:YAG lasers are discussed in Chapter 10, and argon-ion lasers in Section 9.2.)

In re-reading Schawlow and Townes' paper today, there is a clear feeling that viable maser (laser) construction was expected to be very difficult. To everyone's surprise, it turned out to be quite straightforward. Today, lasers have been demonstrated in solid, liquid and plasma, in a variety of metals, as well as in every wavelength (see Figures 1.1 and 1.2).

1.2 THE LASER MARKET

Lasers are used in a number of commercial and research applications. Some of these (such as laser light shows) are dramatic, but involve a relatively small number of lasers. Others (such as laser marking of aluminum) are less well-known, but constitute a significant dollar value of the laser market.

followed by machining and typically small marking, cutting, and welding. Notice that laser applications most commonly cited as dominating the commercial laser market (inspection/measurement, laser printing, and barcode reading) are actually a relatively small dollar-value component of the market as a whole.

Carbon dioxide (CO₂) lasers tend to consistently head the list in dollar volume of sales. This is largely due to strong industrial applications in materials processing (such as laser marking, cutting, and welding). The large economic market tends to disguise the relatively small number of systems sold. In 1993, 4,352 CO₂ laser systems were sold, with 2,780 in laser machining applications, 1,200 in medicine, and 342 in research and development. (Carbon dioxide lasers are discussed in Section 12.1.)

Solid-state lasers have also made a consistent and strong showing over the years, typically second only to CO₂ lasers. Solid-state lasers also find strong markets in laser machining and in medical applications. Again, the relatively high cost of these systems tends to disguise the small volumes. In 1993, 6,320 solid-state laser systems were sold, with 2,430 in laser machining applications, 1,260 in medicine, and 1,815 in research and development. (Solid-state lasers are discussed in more detail in Chapter 10.)

This particular group of dates was selected for two reasons. First, it covers the period when the laser community switched from a primary focus of defense-related research and development to one of commercial application. Second, Laser Focus / Laser Focus World maintained the same type of data base for laser sales over these years. In 1994, Laser Focus / Laser Focus World changed their method of organizing the data, and the results cannot be easily compared with the earlier numbers.
Energy States in Atoms

It is interesting to compare the steady, solid growth of CO$_2$ and solid-state lasers with the decline of ion lasers. Ion laser sales peaked in roughly 1989 and have been dropping ever since. Notice that ion lasers find the largest economic market in research and development, with secondary applications in medicine and in laser printing. Roughly 17,156 ion lasers were sold in 1993, with 5,838 in medical application, 2,588 in research and development, and 5,580 for laser printing and color separation. (Ion lasers are discussed in more detail in Section 9.2.)

Semiconductor diode lasers have shown the most dramatic change over this period. From 1985 to 1992, dollar sales of diode lasers have virtually quadrupled. Unit sales have grown up a factor of twenty, from 2,216,230 in 1985 to 40,022,050 in 1993. Primary applications of diode lasers are in optical memory products (such as audio and digital compact disks) and in laser printing. Notice that the relatively low cost of these units disguises the true differences in magnitude between the laser diode market and any other laser market. In 1993, 40,022,050 laser diodes were sold; 31,500,000 laser diodes specifically for optical memory applications and 7,500,000 specifically for laser printing. (Semiconductor diode lasers are discussed in more detail in Section 12.3.)

An interesting evolution is appearing in the laser market with regard to HeNe lasers and red semiconductor diode lasers. When red semiconductor laser diodes first appeared, it was widely claimed that these diodes would essentially eliminate HeNe lasers as a viable product. However, this has not turned out to be the case. Although HeNe lasers have lost some market share in the barcode scanning arena (compare the peak of 240,000 HeNe units sold for barcode scanning in 1990 to 170,000 in 1993), many test and alignment applications have returned to HeNe lasers due to their better beam quality (compare 57,000 HeNe units sold for alignment test and measurement in 1990 to the 71,000 sold in 1991). (HeNe lasers are discussed in more detail in Section 9.1.)

Excimer lasers have also undergone a change in market over this period. Excimer lasers were originally developed for the research and development market. However, as the research and development market has declined, excimer lasers have moved to more commercial markets. In 1993, 500 excimer systems were sold; 250 for research and development, 180 for medical applications and 70 for laser machining. This compares with 1990 when 560 systems were sold; 390 for research and development, 80 for medical applications and 90 for laser machining. (Excimer lasers are discussed in more detail in Section 12.2.)

At one time lasers were called “a solution looking for a problem.” However, a very healthy recent trend is the reduction in the number of lasers used by the research and development community, and an increase in commercial lasers used for materials processing and medicine. Prior to roughly 1989, the laser industry was largely driven by research and development applications. Today, the increasing number of commercial applications for lasers is providing a sound foundation for the industry as a whole.

1.3 ENERGY STATES IN ATOMS

Lasers can be constructed from solids, liquids, gases, or plasmas. In all cases laser action occurs because photons are emitted as the system transitions between two energy states. In some cases (such as CO$_2$ lasers) these two energy states are two vibrational modes of...
a molecule (see Section 12.1). In other cases (such as semiconductor diode lasers) these two states are the conduction and valence bands of a semiconductor (see Section 12.3). However, in most cases, these two states are electronic states in an atom or ion.

To describe electronic states further, recall that the atom can be modeled as a central nucleus of protons and neutrons surrounded by a cloud of electrons. These electrons can only occupy certain well-defined energy states. These states are organized into groups (often called the main shells of the atom) characterized by the principal quantum number \( n \). Within the main shells, the electrons are further divided into electron orbitals. The simplest orbitals (called s-orbitals) are spherical orbitals that contain two electrons of opposite spins. The more complex p-orbitals are dumbbell-shaped (with a dumbbell in each of the three Cartesian directions) and contain six total electrons. The orbitals after s and p possess increasingly complex shapes and follow the sequence: d, f, g, h, i, k, l, ... (no j!).

The electronic structure of an atom can be expressed by a shorthand notation that describes the principal quantum number, the electron orbital letter, and the number of electrons in each orbital. For example, argon can be expressed as

\[
\text{argon} = 1s^22s^22p^63s^23p^6
\]

and krypton as

\[
\text{krypton} = 1s^22s^22p^63s^23p^63d^104s^24p^6.
\]

In real atoms, the various electron orbitals are divided yet again into sublevels whose energies are determined by more complex interactions within the atom (see Figure 1.5).

Most lasers use transitions between electronic states in the vicinity of the outermost shell of the atom. For example, in the argon-ion laser, laser action occurs when electrons transition from the 4p to the 4s states (see Figure 1.5). These states are significantly higher in energy than the ground state configuration given in Equation (1.1).

Example 1.1

The rare-earth atom neodymium is often used as a dopant in solid-state laser systems. What is the electronic configuration of neodymium?

Solution. The solution can be found in the electronic configuration tables in a chemistry textbook and is found to be

\[
\text{neodymium} = 1s^22s^22p^63s^23p^63d^{10}4s^24p^65s^26s^24f^{13}.
\]

1.4 BASIC STIMULATED EMISSION

1.4.1 Transitions Between Laser States

The word laser is an acronym for Light Amplification by Stimulated Emission of Radiation. It is one of the few acronyms that is now accepted as a word. Thus, the verb forms "to laser" and "lasing" are accepted as real words. (Check a dictionary!)

But, what do the words "light amplification by stimulated emission of radiation" mean?

To answer this, recall how photons are created in an atom. When an electron spontaneously decays from one energy state \( E_2 \) to a lower energy state \( E_1 \), it emits a photon of the energy

\[
E = h\nu = E_2 - E_1
\]

where \( h \) is Planck's constant and \( \nu \) is the frequency of the laser light. This process is called spontaneous emission (see Figure 1.6).

Spontaneous emission does not occur instantaneously. Instead, the electrons reside in the upper energy state for a certain period of time before they spontaneously decay to the lower energy state. The time constant for the spontaneous emission process is termed the spontaneous lifetime.

However, it is also possible to force a transition from one state to another by means of a photon. In other words, a photon of the energy \( h\nu \) can force or stimulate an electron to transfer between states 2 and 1, yielding another photon of the energy \( h\nu = E_2 - E_1 \). This stimulated emission process results in two photons of the energy \( h\nu \). Furthermore, these two photons will be in phase, of the same polarization, and heading in the same direction (see Figure 1.7).
Example 1.2
Consider two energy states, \( E_2 = 2.50 \text{ eV} \) and \( E_1 = 1.0 \text{ eV} \). What is the energy of the photon that is spontaneously emitted between these states? What is the wavelength of the photon?

**Solution.** The energy is given by Equation (1.4) as

\[
E = h \nu = E_2 - E_1 = 2.50 \text{ eV} - 1.0 \text{ eV} = 1.50 \text{ eV}.
\]

The wavelength is determined by rewriting Equation (1.4) as

\[
\lambda = \frac{hc}{E_2 - E_1} = \frac{6.626 \times 10^{-34} \text{ J-sec} \cdot 3 \times 10^8 \text{ m/sec}}{(2.5 \text{ J/coul} - 1.0 \text{ J/coul})(1.602 \times 10^{-19} \text{ coul})} = 827.216 \text{ nm}.
\]

Thus, ideal laser light is formed of groups of photons where all the photons are at exactly the same frequency (wavelength) and all the photons are in phase. Speaking more intuitively, laser light is composed of photons that are all "one color" and all "marching together."

Example 1.3
In laser engineering, problems often arise in the casual use of significant figures. To illustrate the difficulty, perform two calculations for the wavelength of the laser transition between the two energy states, \( E_2 = 2.50 \text{ eV} \) and \( E_1 = 1.0 \text{ eV} \). In the first calculation, use the exact values for \( h \) and \( c \). In the second calculation, use the approximate values \( 6.6 \times 10^{-34} \text{ J-sec} \) and \( 3 \times 10^8 \text{ m/sec.} \)

Solution. Repeating the calculation from Example 1.2:

\[
\lambda = \frac{hc}{E_2 - E_1} = \frac{6.626 \times 10^{-34} \text{ J-sec} \cdot 299,792,458 \text{ m/sec}}{(2.5 \text{ J/coul} - 1.0 \text{ J/coul})(1.602 \times 10^{-19} \text{ coul})} = 826.562 \text{ nm}.
\]

\[
\lambda = \frac{hc}{E_2 - E_1} = \frac{6.6 \times 10^{-34} \text{ J-sec} \cdot 3 \times 10^8 \text{ m/sec}}{(2.5 \text{ J/coul} - 1.0 \text{ J/coul})(1.602 \times 10^{-19} \text{ coul})} = 823.97 \text{ nm}.
\]

In the laser engineering problems, problems often arise in the casual use of significant figures. To illustrate the difficulty, perform two calculations for the wavelength of the laser transition between the two energy states, \( E_2 = 2.50 \text{ eV} \) and \( E_1 = 1.0 \text{ eV} \). In the first calculation, use the exact values for \( h \) and \( c \). In the second calculation, use the approximate values \( 6.6 \times 10^{-34} \text{ J-sec} \) and \( 3 \times 10^8 \text{ m/sec.} \)

Sec. 1.4 Basic Stimulated Emission

1.4.2 Population Inversion

It is only possible to achieve gain in a laser if the population in the upper laser state is greater than the population in the lower laser state. This condition is termed a population inversion. (The physics underlying this process is discussed in more detail in Section 2.2.)

In thermal equilibrium, the population ratio between two states is governed by the Boltzmann equation

\[
\frac{N_2}{N_1} = e^{-\frac{(E_2 - E_1)}{k_B T}}
\]

where \( N_2 \) is the population in the upper state, \( N_1 \) is the population in the lower state, \( k_B \) is Boltzmann's constant, and \( T \) is the temperature.

Notice that the negative sign in the exponent suggests that a population inversion is only permitted under the conditions of "negative temperature." This result was very disturbing to early laser researchers, as negative temperatures are not physically realizable. However, the Boltzmann equation only describes conditions of thermal equilibrium. Lasers are not operated in thermal equilibrium. Instead, the upper state is populated by pumping it via some nonequilibrium process. A pulse of light, an electrical spark or a chemical reaction can all be used to populate the upper laser state.

Example 1.4
Consider two energy states, \( E_2 = 2.10 \text{ eV} \) and \( E_1 = 1.0 \text{ eV} \). Assume that there are \( 1.0 \times 10^{16} \) electrons/cm\(^3\) in \( E_1 \). At a temperature of 10000.0 K, how many electrons are in state \( E_2 \)?

**Solution.** This uses the Boltzmann equation (Equation (1.10)) as

\[
N_2 = N_1 \cdot e^{-\frac{(E_2 - E_1)}{k_B T}}
\]

\[
N_2 = (1.0 \times 10^{16} \text{ electrons/cm}^3) \cdot e^{-\frac{(2.10 \text{ eV} - 1.0 \text{ eV})}{(1.38 \times 10^{-23} \text{ J/K})} \times 10000 \text{ K}}
\]

\[
N_1 = 2.85942 \times 10^{19} \text{ electrons/cm}^3.
\]
Example 1.5
Consider two energy states, $E_2 = 2.10 \text{ eV}$ and $E_1 = 1.0 \text{ eV}$. Assume there are $1.0 \cdot 10^{16}$ electrons/cm$^3$ in $E_2$ and $1.0 \cdot 10^{15}$ electrons/cm$^3$ in $E_1$. What temperature is required to create this population distribution in thermal equilibrium?

Solution. The Boltzmann equation [Equation (1.10)] can be rewritten as

$$ T = \frac{-\left( E_2 - E_1 \right)}{k_B \cdot \ln \left( N_2/N_1 \right)} $$

[Equation (1.14)]

$$ T = \frac{-\left( 2.10 \text{ eV} - 1.0 \text{ eV} \right)}{k_B \cdot \ln \left( 1.0 \cdot 10^{16} \text{ electrons/cm}^3 / 1.0 \cdot 10^{15} \text{ electrons/cm}^3 \right)} $$

[Equation (1.15)]

$$ T = -5543.72 \text{ K} $$

[Equation (1.16)]

Notice the negative temperature! This situation will not occur in thermal equilibrium, as negative temperatures are not physically realizable. However, similar population ratios are quite common in real laser systems under nonequilibrium pumping conditions.

1.5 POWER AND ENERGY
Lasers can operate either in a continuous wave (cw) or a pulsed mode. Pulsed operation is occasionally performed to reduce the heating of the laser (common for semiconductor diode lasers). However, in most cases, pulsed operation is combined with techniques such as Q-switching (which concentrates the laser energy into the pulse) and mode-locking (which shortens the width of the pulse in time). Q-switched, mode-locked lasers have the ability to concentrate very high peak power densities due to the relatively short length of the pulse. (For more information on Q-switching and mode-locking, see Sections 6.2 and 6.4.)

Some care must be taken in discussing the properties of pulsed versus cw lasers, as the use of watts (to describe peak power) can be easily confused with the use of watts (to describe average power). In this text, the following definitions will be used.

**Average power:** The power (in watts) of a continuous wave laser, or the energy per pulse (J) times the pulse repetition rate (Hz) for pulsed lasers as

$$ P_{\text{avg}} = E_{\text{pulse}} \cdot R_{\text{repeate}} $$

[Equation (1.17)]

**Peak power:** The energy per pulse (J) divided by the temporal length of the pulse (seconds) as

$$ P_{\text{peak}} = \frac{E_{\text{pulse}}}{t_{\text{pulse}}} $$

[Equation (1.18)]

**Average energy density:** The energy (joules) per unit area (cm$^2$ or m$^2$).

**Average power density:** The average power (watts) per unit area (cm$^2$ or m$^2$).

**Peak power density:** The peak power (watts) per unit area (cm$^2$ or m$^2$).

1.6 MONOCHROMATICITY, COHERENCY, AND LINEWIDTH

The property of having a group of photons at exactly one frequency is referred to as monochromaticity. The property of having a group of photons with the same relative phase is referred to as coherency. Thus, lasers are often termed monochromatic and coherent sources of light (see Figure 1.8). (Notice that this is a redundant definition for an ideal laser, because a perfectly coherent source of light must be monochromatic. However, notice also that a perfectly monochromatic source of light, such as spontaneous emission, need not be coherent!) Typically, the "color" of a laser beam is characterized by the center wavelength of the laser line. In actual practice, both wavelength $\lambda$ (in angstroms or nm) and frequency $\nu$ (in

\[ \text{Figure 1.8 An ideal monochromatic source of light has a group of photons with exactly one frequency. An ideal coherent source of light has a group of photons with the same relative phase.} \]
Hz) are used. Thus, the center wavelength $\lambda$ of a laser line could be expressed in terms of frequency $\nu$ as

$$\lambda = \frac{c_0}{\nu}. \quad (1.24)$$

Of course, real lasers are neither perfectly monochromatic nor perfectly coherent (see Figure 1.9). However, when characterizing a real laser system, it is generally assumed that the laser beam was initially in phase and the incoherence of the laser arises only from the lack of monochromaticity of the source. (This is a reasonable assumption for conventional lasers with feedback, but may not be sufficiently accurate for unusual laser systems.) Thus, coherency and monochromaticity are generally assumed to measure the same parameter.

The monochromaticity of a laser beam is described by its \textit{wavelength linewidth} $\Delta \lambda$ (in angstroms or nm) or its \textit{frequency linewidth} $\Delta \nu$ (in Hz). The two quantities are related as

$$\Delta \nu = \nu_1 - \nu_2 = \frac{\lambda_1}{\lambda_2} - \frac{\lambda_2}{\lambda_1} = \frac{\lambda_2 - \lambda_1}{\lambda_1 \lambda_2}$$

(1.25)

which (assuming that $\lambda_1$ and $\lambda_2$ are much larger than $\lambda_2 - \lambda_1$) can be approximated by

$$\Delta \nu = \nu_1 - \nu_2 \approx c_0 \left( \frac{\Delta \lambda}{\lambda^2} \right). \quad (1.26)$$

The fundamental linewidth for an ideal laser line is extremely small.\(^{27}\) In practice, various \textit{broadening mechanisms} will increase this fundamental linewidth in real lasers (see Section 2.1).

The monochromaticity of a laser beam can also be described in terms of coherence. Notice that the length of time it takes for two oscillations differing in frequency by $\Delta \nu$ to get out of phase by a full cycle is approximately $1/\Delta \nu$. Thus, the \textit{coherence time} $\delta \tau$ is given by

$$\delta \tau = \frac{1}{\Delta \nu}. \quad (1.27)$$

and the \textit{coherence length} $l_c$ is expressed as

$$l_c = c_0 \cdot \delta \tau = \frac{c_0}{\Delta \nu}. \quad (1.28)$$

**Example 1.7**

Consider an argon-ion laser with a center wavelength of 514.5 nm. Calculate the energy of the laser transition in eV, the frequency of the transition in Hz, and the spectroscopic wavenumber ($1/\lambda$) in cm\(^{-1}\).

**Solution.** The transition energy is determined by rewriting Equation (1.4) as

$$E_2 - E_1 = \frac{\hbar c_2}{\lambda} = \frac{\hbar c_2}{514.5 \cdot 10^{-9} \text{ m}} = 2.4098 \text{ eV}. \quad (1.29)$$

The optical frequency is determined by rewriting Equation (1.24) as

$$\nu = \frac{c_2}{\lambda} = \frac{c_2}{514.5 \cdot 10^{-9} \text{ m}} = 5.827 \cdot 10^{14} \text{ Hz} = 582.7 \text{ THz}. \quad (1.30)$$

The spectroscopic wavenumber is determined by simply inverting the wavelength as

$$\nu = \frac{1}{\lambda} = \frac{1}{514.5 \cdot 10^{-9} \text{ m}} = 19436 \text{ cm}^{-1}. \quad (1.31)$$

**Example 1.8**

Consider a semiconductor laser diode with a laser linewidth of 2.0 angstroms and a center operating wavelength of 870 nm. What is the frequency linewidth $\Delta \nu$ in Hz?

**Solution.** This uses Equation (1.26). Substituting in the relevant parameters gives

$$\Delta \nu \approx c_0 \left( \frac{\Delta \lambda}{\lambda^2} \right) = c_0 \left( \frac{2.0 \cdot 10^{-10} \text{ m}}{(870 \cdot 10^{-9} \text{ m})^2} \right) = 79.2 \text{ GHz}. \quad (1.32)$$

**Example 1.9**

Consider a HeNe laser with a linewidth of 1.50 GHz and a center operating wavelength of 632.8 nm. What is the laser linewidth $\Delta \lambda$ in angstroms?

**Solution.** This uses Equation (1.26) reorganized as

$$\Delta \lambda \approx \lambda^2 \left( \frac{\Delta \nu}{c_0} \right). \quad (1.33)$$

Substituting in the relevant parameters gives

$$\Delta \lambda \approx \lambda^2 \left( \frac{\Delta \nu}{c_0} \right) = (632.8 \cdot 10^{-9} \text{ m})^2 \left( \frac{1.5 \cdot 10^9 \text{ Hz}}{c_0} \right) = 0.002004 \text{ nm}. \quad (1.34)$$
Example 1.10
Consider a Nd:YAG laser with a laser linewidth of 4.50 angstroms and a center operating wavelength of 1.064 μm. What is its coherence length?

Solution. This uses Equation (1.26) to determine the linewidth in Hz. Substituting in the relevant parameters gives

\[ \Delta \nu \approx c_e \left( \frac{\Delta \lambda}{\lambda^2} \right) = c_e \left( \frac{4.5 \cdot 10^{-16} \text{ m}}{(1.064 \cdot 10^{-6} \text{ m})^2} \right) = 119.17 \text{ GHz.} \]  

The coherence length is then determined by Equation (1.28) as

\[ l_c = \frac{c_e}{\Delta \nu} = \frac{c_e}{119.16 \text{ GHz}} = 2.516 \text{ mm.} \]

Example 1.11
The uninitiated observer might confuse the center frequency of the laser line \( \nu \) (in Hz) with the laser linewidth \( \Delta \nu \) (also in Hz). However, the two numbers differ significantly in magnitude. To demonstrate this, calculate the center frequency \( \nu \) (in Hz) and the laser linewidth \( \Delta \nu \) (in Hz) for a semiconductor diode laser with a center operating wavelength of 760 nm and a laser linewidth \( \Delta \lambda \) of 3.0 angstroms.

Solution. The center wavelength can be converted to frequency units by using equation (1.24). For the semiconductor diode laser of Example 1.1, this yields

\[ \nu = \frac{c_e}{\lambda} = \frac{c_e}{760 \cdot 10^{-9} \text{ m}} = 3.945 \cdot 10^{14} \text{ Hz} = 394.5 \text{ THz.} \]  

The laser linewidth uses Equation (1.26). Substituting in the relevant parameters gives

\[ \Delta \nu \approx c_e \left( \frac{\Delta \lambda}{\lambda^2} \right) = c_e \left( \frac{3.0 \cdot 10^{-16} \text{ m}}{(760 \cdot 10^{-9} \text{ m})^2} \right) = 155.7 \text{ GHz.} \]

Notice that the center frequency \( \nu \) will be on the order of many THz. The laser linewidth \( \Delta \nu \) of most lasers is on the order of MHz to GHz. Thus, the two numbers differ by many orders of magnitude!

1.7 SPATIAL COHERENCE AND LASER SPECKLE

Spatial coherence is another important property of laser systems. To understand spatial coherence, imagine a beam of constant intensity propagating in the \( z \) direction. Consider any two points \( P_1 \) and \( P_2 \) on the beam chosen in a plane perpendicular to the \( z \)-axis (see Figure 1.10). If the relative phase difference measured between the two points \( P_1 \) and \( P_2 \) is constant in time, then the beam is termed spatially coherent.

Notice that spatial coherence does not require photon coherence. Thus spatial coherence is not a direct result of the laser action, but is actually a property of the electromagnetic modes of the laser. (For example, spatially coherent light can be obtained by shining sunlight through a pinhole.) However, lasers offer the highest intensity sources of spatially coherent light and thus are used in applications (such as holography and interferometry) that require spatially coherent sources (see Section 9.1 for more information on these applications).

1.8 THE GENERIC LASER

Most lasers are constructed of three important elements, a gain material, a pumping source and a resonant cavity (see Figure 1.11).

The gain material is the location of the energy states which participate in stimulated emission. The material can be solid (Nd:YAG, ruby, GGG, GSGG, alexandrite, emerald, Cr:sapphire, Ti:sapphire, AlGaAs/GaAs, etc.; see Chapters 10 and 11); liquid (dye, chelate, etc.), gas (krypton, argon, nitrogen, helium-neon, CO₂, KrF, XeCl, etc.; see Sections 9.1, 9.2, 12.1, and 12.2), or plasma (x-ray, free-electron, etc.).

The pumping source provides the energy to set up the energy states so that stimulated emission can occur. Lasers can be optically pumped using lamps or other lasers (most solid-state lasers, see Chapters 10 and 11), electrically pumped using a pn-junction (semiconductor diodes, see Section 12.3) or an electric discharge (most gas lasers, see Sections 9.1 and 9.2), or pumped by a chemical reaction (HF, iodine, etc.). Lasers have even been pumped by such dramatic methods as jet engines (gasdynamic CO₂ lasers, see Section 12.1) or atomic bombs (x-ray lasers).
Most lasers are constructed from three important elements: a gain material, a pumping source, and a resonant cavity. Figure 1.11

The functions of the folded resonant cavity are to physically shorten the laser and tailor the profile of the electromagnetic mode.

The resonant cavity provides a regenerative path for the photons. In essence, the functions of the resonant cavity are to 1) physically shorten the laser, and 2) tailor the profile of the electromagnetic mode. (General resonant cavity design is discussed in Chapter 4.)

In some sense, the laser is simply "folded up" between the two resonant cavity mirrors (see Figure 1.12). Although the resonant cavity is a key part of most commercial lasers, there are many lasers for which the resonant cavity is not necessary. It is certainly possible to make a laser long enough so that a reasonable intensity of light beam emerges without a resonant cavity (most x-ray lasers are made this way). However, such lasers tend to have poor output-beam quality.

1.9 TRANSVERSE AND LONGITUDINAL MODES

The output spot of the laser beam is termed the transverse electromagnetic mode (TEM). In most commercial lasers the transverse electromagnetic mode is TEM₀,₀ (see Figure 1.13), which is a round mode with a Gaussian profile in cross-section. (The TEM₀,₀ mode is discussed in more detail in Section 4.3.)

However, it is possible to operate on a wide variety of other transverse mode configurations (see Section 4.2). In these configurations, the output spot will have a much more peculiar shape (see Figure 1.14).

A laser can only lase at those wavelengths for which an integral multiple of half-wavelengths precisely fit into the cavity (see Figure 1.15). The set of possible integral multiples of the cavity length is termed the set of longitudinal electromagnetic modes of the cavity (or simply the longitudinal modes). The frequencies of these modes are given by

\[ v = \frac{p \cdot c}{2nL} \quad \text{where} \quad p = 1, 2, 3, \ldots \]

Figure 1.13 In most commercial lasers the transverse mode is TEM₀,₀, which is a round mode with a Gaussian profile in cross-section.

Figure 1.14 It is possible to operate a laser with a wide variety of other transverse electromagnetic modes.
where \( n \) is the index of refraction in the cavity and \( L \) is the cavity length. Notice that \( p \) will be a very large number in a typical laser system (see Section 3.1).

The longitudinal mode spacing is frequently of interest in designing or using a laser system. The longitudinal mode spacing is given as

\[
\Delta \nu_{\text{SR}} = \frac{c_0}{2nL} 
\]

(1.40)

Example 1.12

An argon-ion laser with a 1.0 meter resonant cavity is lasing with a center wavelength (in vacuum) at 488 nm. What is the mode number \( p \) for the mode closest to 488 nm? (Assume that the index of refraction for the cavity is 1.0.)

Solution. This uses Equation (1.39) reorganized as

\[
p = \frac{2nL}{\lambda} = \frac{2 \cdot 1.0 \cdot 1.0 \text{ m}}{\lambda} = 4098360.65 \rightarrow 4098361
\]

(1.41)

which may be verified by using equation (1.39),

\[
\lambda = \frac{2nL}{p} = \frac{2 \cdot 1.0 \cdot 1.0 \text{ m}}{4098361} = 487.999959 \cdot 10^{-9} \text{ m.}
\]

(1.42)

Example 1.13

A HeNe laser with a 30.0 cm resonant cavity is lasing with a center wavelength (in vacuum) at 632.8 nm. What is the longitudinal mode spacing (in Hz)? (Assume that the index of refraction for the cavity is 1.0)

Solution. This uses Equation (1.40) as

\[
\Delta \nu_{\text{SR}} = \frac{c_0}{2nL} = \frac{c_0}{2 \cdot 1.0 \cdot 0.30 \text{ m}} = 499.654 \text{ MHz.}
\]

(1.43)

1.10 THE GAIN PROFILE

A particular laser material does not have gain at all frequencies. The function that describes the frequency dependence of the gain is termed the gain profile \( g(\nu) \) (see Figure 1.16). (The gain profile is discussed in more detail in Section 2.1.)
1.11 LASER SAFETY

Laser safety is an extremely important part of laser engineering—not only in using lasers, but in designing lasers and laser systems to be used by others. The Appendix presents a discussion of laser safety for laser courses with an included laboratory. For more information on laser safety issues, the reader is strongly encouraged to obtain a copy of the ANSI publication ANSI Z136.1-1993 (American National Standard for the Safe Use of Lasers). Additionally there are a number of excellent references that are specifically directed toward the issues of laser safety.28

28Published by the Laser Institute of America.

Figure 1.18 There is a center wavelength for the gain profile and its corresponding frequency, a center wavelength for each longitudinal mode and their corresponding frequencies, a linewidth for the gain profile, a linewidth for each longitudinal mode, and a longitudinal mode separation.

SYMBOLS USED IN THE CHAPTER

s.p,d,f: Notation for electron orbitals
E: Photon energy (joules or eV)
E2 and E1: Upper and lower laser state energies (joules or eV)
\(v\): Nonspecific frequency (Hz)
\(\lambda\): Nonspecific wavelength in a material (cm or m)
\(N_2\) and \(N_1\): Upper and lower laser state populations (electrons/cm\(^3\))
\(T\): Temperature (degrees K)
\(E_{\text{pulse}}\): Energy per pulse (joules)
\(R_{\text{repmax}}\): Repetition rate (Hz)
\(P_{\text{avg}}\): Average power (watts)
\(P_{\text{peak}}\): Peak power (energy/pulse width) (watts)
\(t_{\text{pulse}}\): Pulse width (seconds)
\(E_{\text{den}}\): Energy per unit area (joules/cm\(^2\))
\(P_{\text{peak-den}}\): Peak power per unit area (watts/cm\(^2\))
\(P_{\text{avg-den}}\): Average power per unit area (watts/cm\(^2\))
\(v_{\text{g}}, \lambda_{\text{g}}\): Frequency and wavelength at the center of the gain curve
\(v_{\text{m}}, \lambda_{\text{m}}\): Frequency and wavelength at the center of a particular longitudinal mode (Hz, and m or mm)
\(\Delta v, \Delta \lambda\): Frequency and wavelength linewidths at the center of the gain curve (Hz, and m or mm)
\(\Delta v_{\text{g}}, \Delta \lambda_{\text{g}}\): Frequency and wavelength linewidths of a particular longitudinal mode (Hz, and m or mm)
\(\Delta v_{\text{FSR}}, \Delta \lambda_{\text{FSR}}\): Frequency and wavelength spacings between longitudinal modes (Hz, and m or mm)
\(t_{\text{cav}}\): Cavity decay time (seconds)
\(P_{\text{out}}\): Output laser power (watts)
\(\delta t\): Coherence time (seconds)
\(L\): Coherence length (cm or m)
\(\omega_{\text{FSR}}\): Spectroscopic wavenumber (1/\(\lambda\)) (cm\(^{-1}\))
P2 and P1: Locations on a wavefront
\(L\): Length of a resonant cavity (cm or m)
\(p\): Integer describing the “number” of a particular longitudinal mode
\(n\): Real index of refraction (unitless)
EXERCISES

Basics

1.1 (a) Describe briefly the difference between a penlight laser and a penlight flashlight.
   (b) Propose a simple test to differentiate a penlight laser from a penlight flashlight.

1.2 The United Federation of Planets starship Voyager is armed with phasors and photon torpedoes. Explain (citing fundamental physical principles as appropriate) why neither phasors nor photon torpedoes are advanced versions of lasers. (For those who are not Trekkies, phasors and photon torpedoes are fictional weapons from Star Trek. A phasor can be set to "stun" or "kill": an individual shot by a phasor on "stun" falls over in a faint; on "kill" the person is vaporized. Phasors usually appear orange on the TV screen and can be seen to visually travel from the source to target. Photon torpedoes are round objects shot from the starship. They impact on the target and it explodes. They also can be seen to visually travel from the source to target.)

1.3 Construct a logarithmic wavelength-frequency scale for electromagnetic radiation. Mark both frequency and wavelength on the x-axis of the scale in appropriate units (nm, μm, cm, m, etc.) and (Hz, kHz, GHz, etc.). On the scale indicate the following regions:
   a. visible light (include red, yellow and blue),
   b. AM radio, c. FM radio, d. x-rays, e. gamma rays, f. S- and X-band traffic radar, and g. TV.

1.4 Complete the following table for various types of electromagnetic radiation.

<table>
<thead>
<tr>
<th>Center wavelength, λ</th>
<th>Center frequency, ν</th>
</tr>
</thead>
<tbody>
<tr>
<td>Red light 650 nm</td>
<td>571 THz</td>
</tr>
<tr>
<td>Green light 450 nm</td>
<td>517 THz</td>
</tr>
<tr>
<td>Blue light 450 nm</td>
<td></td>
</tr>
<tr>
<td>Yellow light 560.3 m-186.8 m</td>
<td>88 MHz-108 MHz</td>
</tr>
<tr>
<td>AM radio</td>
<td></td>
</tr>
<tr>
<td>FM radio</td>
<td></td>
</tr>
<tr>
<td>X-rays 0.1-100 Å</td>
<td>&gt; 3 · 10¹⁹ Hz</td>
</tr>
<tr>
<td>Gamma rays</td>
<td></td>
</tr>
<tr>
<td>Near infrared 800 nm-5 μm</td>
<td></td>
</tr>
<tr>
<td>S-band radar</td>
<td>2 GHz-4 GHz</td>
</tr>
<tr>
<td>TV channels 7-13</td>
<td>1.72 m-1.38 m</td>
</tr>
</tbody>
</table>

Transitions between laser states

1.5 There are a number of ways of specifying the separation between two laser states. These include the energy difference $E_2 - E_1$, in joules or eV, the wavelength $λ$ (in angstroms, nm or microns), the frequency $ν$ (in Hz) and the spectroscopic wavenumber ($1/λ$ in cm⁻¹). Determine appropriate conversion equations for all quantities and complete the following table.

(a) General lasers

<table>
<thead>
<tr>
<th>$E$ (eV)</th>
<th>$E$ (J)</th>
<th>$λ$ (nm)</th>
<th>$ν$ (Hz)</th>
<th>$1/λ$ (cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>XeCl</td>
<td>4.025</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coumarin-2</td>
<td>4.414 · 10⁻¹⁹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argon-ion</td>
<td>514.5</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ti:sapphire</td>
<td>3.944 · 10⁻¹⁴</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>9398.5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(b) Gas and excimer lasers

<table>
<thead>
<tr>
<th>$E$ (eV)</th>
<th>$E$ (J)</th>
<th>$λ$ (nm)</th>
<th>$ν$ (Hz)</th>
<th>$1/λ$ (cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KrF</td>
<td>4.979</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>XeF</td>
<td>5.695 · 10⁻¹⁹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Argon-ion</td>
<td>488.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HeNe-IR</td>
<td>2.607 · 10¹⁴</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CO₂</td>
<td>943.396</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(c) Dye lasers

<table>
<thead>
<tr>
<th>$E$ (eV)</th>
<th>$E$ (J)</th>
<th>$λ$ (nm)</th>
<th>$ν$ (Hz)</th>
<th>$1/λ$ (cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coumarin-102</td>
<td>2.53</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coumarin-7</td>
<td>4.169 · 10⁻¹⁹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rhodamine 110</td>
<td>570.0</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cresyl violet</td>
<td>4.409 · 10¹⁴</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nile blue-A</td>
<td>13698.6</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(d) Solid-state and semiconductor diode lasers

<table>
<thead>
<tr>
<th>$E$ (eV)</th>
<th>$E$ (J)</th>
<th>$λ$ (nm)</th>
<th>$ν$ (Hz)</th>
<th>$1/λ$ (cm⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlGaAs</td>
<td>1.589</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nd:YLF</td>
<td>1.886 · 10⁻¹⁹</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nd:glass (LHG-8)</td>
<td>1054</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nd:glass (LG-670)</td>
<td>2.826 · 10¹⁴</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Er:YAG</td>
<td>3401.36</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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(e) More solid-state and semiconductor diode lasers

<table>
<thead>
<tr>
<th>Laser</th>
<th>$E$ (eV)</th>
<th>$E$ (J)</th>
<th>$\lambda$ (nm)</th>
<th>$\nu$ (Hz)</th>
<th>$1/\lambda$ (cm$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>AlGaAs</td>
<td>1.851</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ruby</td>
<td>$2.861 \times 10^{-19}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Alexandrite</td>
<td>760</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cr:LiSAF</td>
<td>3.568 x 10$^{14}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Er:glass</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>6493.51</td>
</tr>
</tbody>
</table>

Population inversion

1.6 Two energy levels $E_2$ and $E_1$ are separated by an energy gap $E_2 - E_1$. Evaluate the ratio $N_2/N_1$ (where $N_2$ is the population in level $E_2$ and $N_1$ is the population in level $E_1$) for the following cases.

<table>
<thead>
<tr>
<th>$T$(K)</th>
<th>Energy gap</th>
<th>$N_2/N_1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>6328 Å</td>
<td></td>
</tr>
<tr>
<td>1000</td>
<td>6328 Å</td>
<td></td>
</tr>
</tbody>
</table>

1.7 Two energy levels $E_2$ and $E_1$ are separated by an energy gap $E_2 - E_1$. Evaluate the temperature that gives the specific population ratio $N_2/N_1$ (where $N_2$ is the population in level $E_2$ and $N_1$ is the population in level $E_1$) for the following cases.

<table>
<thead>
<tr>
<th>$N_2/N_1$</th>
<th>Energy gap</th>
<th>$T$(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>6328 Å</td>
<td></td>
</tr>
<tr>
<td>0.01</td>
<td>6328 Å</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>6328 Å</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>6328 Å</td>
<td></td>
</tr>
<tr>
<td>0.1</td>
<td>6328 Å</td>
<td></td>
</tr>
</tbody>
</table>

Power and energy

1.8 (a) A Nd:YAG laser has an energy of 0.4 joules/pulse, a repetition rate of 30 Hz, a pulsewidth of 20 nsec and has been focused into a spot of radius 0.5 mm. Calculate the average and peak power of the laser. Also calculate the energy density and the peak power density at the focus.

1.9 Gain linewidth for lasers ($\Delta \nu_g$, $\Delta \lambda_g$) are often measured in angstroms if they are large and in Hz if they are small (see Figure 1.19). Complete the following table.

<table>
<thead>
<tr>
<th>wavelength, $\lambda$</th>
<th>$\Delta \nu_g$(Hz)</th>
<th>$\Delta \lambda_g$(Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nd:YAG</td>
<td>1.064 μm</td>
<td>300 GHz</td>
</tr>
<tr>
<td>Nd:glass</td>
<td>1.055 μm</td>
<td>24.13 Å</td>
</tr>
<tr>
<td>HeNe</td>
<td>632.8 nm</td>
<td>1500 MHz</td>
</tr>
<tr>
<td>GaAs - diode</td>
<td>780.0 nm</td>
<td>81.17 Å</td>
</tr>
</tbody>
</table>

Linewidth

1.10 A laser spectrum is composed of a number of longitudinal modes. These modes are separated by the longitudinal mode spacing ($\Delta \nu_{sr}$, $\Delta \lambda_{sr}$) of the laser cavity. The total linewidth of the gain curve ($\Delta \nu_g$, $\Delta \lambda_g$) is the envelope of these modes (see Figure 1.20). Assuming that the index of refraction is equal to air ($n = 1$) in all cases, complete the following tables.
(a) Major commercial HeNe lines

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>L (cm)</th>
<th>ΔνFSR (Hz)</th>
<th>ΔλFSR (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Green</td>
<td>543.5</td>
<td>22.4</td>
<td></td>
</tr>
<tr>
<td>Yellow</td>
<td>594.1</td>
<td>26.4</td>
<td></td>
</tr>
<tr>
<td>Orange</td>
<td>612.0</td>
<td>35.7</td>
<td></td>
</tr>
<tr>
<td>Red</td>
<td>632.8</td>
<td>25.1</td>
<td></td>
</tr>
<tr>
<td>Near IR</td>
<td>1150.0</td>
<td>20.3</td>
<td></td>
</tr>
<tr>
<td>Fiber-optic IR</td>
<td>1523.0</td>
<td>24.8</td>
<td></td>
</tr>
<tr>
<td>IR</td>
<td>3390.0</td>
<td>34.9</td>
<td></td>
</tr>
</tbody>
</table>

(b) Major commercial argon-ion laser lines

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>L (cm)</th>
<th>ΔνFSR (Hz)</th>
<th>ΔλFSR (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>465.8</td>
<td>65.5</td>
<td></td>
</tr>
<tr>
<td>Blue-green</td>
<td>472.7</td>
<td>71.1</td>
<td></td>
</tr>
<tr>
<td>Blue-green</td>
<td>476.5</td>
<td>71.1</td>
<td></td>
</tr>
<tr>
<td>Blue-green</td>
<td>488.0</td>
<td>73.9</td>
<td></td>
</tr>
<tr>
<td>Blue-green</td>
<td>496.5</td>
<td>78.7</td>
<td></td>
</tr>
<tr>
<td>Green</td>
<td>501.7</td>
<td>88.4</td>
<td></td>
</tr>
<tr>
<td>Emerald green</td>
<td>514.5</td>
<td>93.5</td>
<td></td>
</tr>
</tbody>
</table>

(c) Major solid-state laser materials

<table>
<thead>
<tr>
<th>λ (nm)</th>
<th>L (cm)</th>
<th>ΔνFSR (Hz)</th>
<th>ΔλFSR (Å)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ruby</td>
<td>694.3</td>
<td>68.2</td>
<td></td>
</tr>
<tr>
<td>Ti:sapphire</td>
<td>760</td>
<td>75.2</td>
<td></td>
</tr>
<tr>
<td>Cr:LiSAF</td>
<td>840</td>
<td>87.4</td>
<td></td>
</tr>
<tr>
<td>Nd:YLF</td>
<td>1053.0</td>
<td>59.4</td>
<td></td>
</tr>
<tr>
<td>Nd:glass (LHG-5)</td>
<td>1053.0</td>
<td>63.8</td>
<td></td>
</tr>
<tr>
<td>Nd:glass (ED-2)</td>
<td>1062.3</td>
<td>79.1</td>
<td></td>
</tr>
<tr>
<td>Nd:YAG</td>
<td>1064.0</td>
<td>85.9</td>
<td></td>
</tr>
</tbody>
</table>

Exercises

Review of basic optics—Lenses

1.11 The following are simple review lens problems.

(a) Consider a convex glass lens where the radius of the front surface is 25 cm and the radius of the back surface is 40 cm. Assume that the index of refraction is 1.5. What is the focal length of the lens? Repeat the calculation assuming the lens is concave.

(b) Consider a plano-convex lens, where the radius of the back surface is 50 cm. Assume that the index of refraction is 1.5. What is the focal length of the lens? Repeat the calculation assuming the lens is plano-concave.

(c) Consider a meniscus convex glass lens where the radius of the front surface is 25 cm and the radius of the back surface is -40 cm. Assume that the index of refraction is 1.5. What is the focal length of the lens?

(d) Consider a meniscus concave glass lens where the radius of the front surface is 50 cm and the radius of the back surface is -30 cm. Assume that the index of refraction is 1.5. What is the focal length of the lens?

(e) Consider a convex lens with a focal length of 50 cm. If a point source is placed 65 cm in front of the lens, where is the image located? If the point source is moved to a distance 15 cm from the front of the lens, where is the image now located?

(f) Consider a concave lens with a focal length of -50 cm. If a point source is placed 65 cm in front of the lens, where is the image located? If the point source is moved to a distance 15 cm from the front of the lens, where is the image now located?

Review of basic optics—Telescope problems

1.12 Consider a telescope similar to Figure A.4. Assume that the front lens is convex with a focal length of 50 cm. Assume that the lenses are separated by 1 meter and that the image is located a distance of 30 cm from the front of first lens. Calculate the location of the object. Is this a real or virtual object?

1.13 Consider a telescope similar to Figure A.5. Assume that the front lens is concave with a focal length of -20 cm. Assume that the lenses are separated by 70 cm and that the image is located a distance of 25 cm from the front of first lens. Calculate the location of the object. Is this a real or virtual object?

1.14 Consider a telescope similar to Figure A.4. Assume that the front lens is convex with a focal length of 40 cm. Assume the input beam is collimated.

(a) Plot the location of the focus spot as the distance separating the lenses is varied from 0 to 250 cm.

(b) Discuss the plot in terms of the laboratory construction of a small telescope to be used as a beam expander.

1.15 Consider a telescope similar to Figure A.5. Assume that the front lens is concave with a focal length of -30 cm. Assume the back lens is convex with a focal length of 100 cm. Assume the input beam is collimated.

(a) Plot the location of the focus spot as the distance separating the lenses is varied from 0 to 250 cm.

(b) Discuss the graph in terms of laboratory construction of a small telescope to be used as a beam expander.
Review of basic optics—Reflection and refraction

1.16 Consider the situation where a laser beam is traveling from one material to another material. Assume the incident angle is 15 degrees from the normal. In each of the three cases, calculate the reflected and transmitted angle (as measured from the normal) and create a sketch (roughly to scale) of the incident, reflected and refracted rays.

(a) A laser beam traveling in ethanol (n = 1.361) that enters a fused silica block (n = 1.458).
(b) A laser beam traveling in gallium arsenide (n = 3.655) that enters air (n = 1).
(c) A laser beam traveling in lithium niobate (n = 2.094) that enters water (n = 1.33).

1.17 Two polar bears are on display at the Point Defiance Park Zoo (see Figure 1.21). Their habitat contains a large pool with a window. (They spend a great deal of time playing in the pool.) The window into the habitat is oriented so that visitors can see both the underwater and above-water scene. For example, when the bears are mock-fighting in the water, the visitors can see both the bears’ heads (above water) and the bears’ bodies (below water). However, when standing in the viewing area, the polar bears’ heads (as viewed above the water) are offset from their bodies (as viewed below the water). When children come into the viewing area, they always think there are four bears because the heads are offset significantly from the bodies. Calculate the distance that the heads are apparently offset from the bodies.

1.18 Brewster’s angle

It is quite common to insert optical components inside a laser cavity at Brewster’s angle to minimize the reflection of the p or || polarization component (see Figure 1.22).

(a) Calculate the length of the major axis (2a) of the beam image on the optical surface, assuming that the optical element is a piece of quartz (index of refraction = 1.458). Assume that the beam diameter is 10 mm.
(b) Calculate the length of the major axis (2a) of the beam image on the optical surface, assuming that the optical element is a piece of lithium niobate (index of refraction = 2.094). Assume that the beam diameter is 10 mm.

1.19 Consider the method of separating real diamonds from fake diamonds by dropping them in olive oil. The idea is that real diamonds can still be seen and fake diamonds “vanish.”

(a) Calculate the intensity reflection at normal incidence for diamonds (n = 2.41) in olive oil (n = 1.4679).
(b) Calculate the intensity reflection at normal incidence for lead glass (n = 1.6) in olive oil.
(c) YAG is also used as simulated diamond. Calculate the intensity reflection at normal incidence for YAG (n = 1.82) in olive oil.
(d) Do you think that this separation method works? Explain why or why not.

1.20 Consider a glass microscope slide suspended in the center of an aquarium full of water. Assume a randomly polarized laser beam is traveling through the aquarium and intersects the microscope slide. Calculate the parallel and perpendicular polarization reflectances of the laser beam from the microscope slide assuming the slide is at 25 degrees to the laser beam (25 degrees from normal). Assume the microscope slide has an index of refraction of n = 1.55.

1.21 Use of computer program (e.g., Mathematica, Maple, MatLab, MathCad, Lotus 123, Excel) to generate a plot of the reflection and transmission coefficients for parallel and perpendicular polarizations (a plot similar to Figure A.8). However, assume that the material is YAG with an index of refraction n = 1.82.

1.22 Use a computer program (e.g., Mathematica, Maple, MatLab, MathCad, Lotus 123, Excel) to generate a plot of the reflection and transmission coefficients for parallel and perpendicular polarizations. However, instead of having the x-axis represent \( \theta \), have the x-axis represent index of refraction (n). Plot the reflectance and transmittance for both polarizations at \( \theta = n = 25 \) degrees assuming an index of refraction range of 1.0–4.0. Assume \( n = 1.0 \).