Chapter 2

Basic Concepts

The concepts related to lasers and optical physics presented in this chapter are discussed in descriptive rather than analytical terms. Although much of the discussion is quite basic, it masks the complex and often elegant underlying mathematics. Such treatment has its limitations but is designed to provide the necessary insight to the reader with only a general background in optics. For an in-depth discussion of the subject matter there are several comprehensive texts on laser physics [See, for example, *Lasers* by A.E. Siegman, University Science Books, Mill Valley, (1986).]

2.1 Lasers

Lasers are devices that generate coherent optical radiation. The word "laser" is an acronym for "light amplification by stimulated emission of radiation." The laser is used in a variety of applications, and lasers have been demonstrated that incorporate an extraordinary range of gain elements, pumping methods, and resonator designs. The main characteristics of lasers, which determine the scope of applications, are coherence, directionality, monochromaticity, and intensity (brightness).

In order to achieve laser action, a device must contain a gain element located in an optical resonator. The gain element is referred to as the "laser material" or "gain medium" and is what produces amplification by stimulated emission. The laser itself is named for the gain element. For example, a "dye laser" uses a dye solution as the gain medium, while the gain element in an "Nd:YAG" laser is composed of trivalent neodymium ions doped in an yttrium aluminum garnet ("YAG") crystalline host.

The gain element is composed of a material that is able to support a population inversion when excited. A photon passing through a gain element has a higher probability of producing a second photon (at the same wavelength) by stimulated emission than it has of being absorbed. The requirements for producing a population inversion vary for different types of excitation techniques. In this book we are concerned only with optical excitation—more specifically, with laser diode pumping. Thus, we need to specify the optical pump conditions that enable the laser diode(s) to produce a population inversion.

A resonator is required for the generation of optical feedback. Without feedback the gain element provides optical amplification but not the directionality associated with laser emission. (Even when located within a resonator, however, the gain element may have sufficient single-pass gain to produce amplified spontaneous emission, or ASE). A gain element lacking feedback can be used as an optical amplifier for light from a low-power laser. However, in order to achieve laser action the gain element must have optical feedback.

An optical resonator consists of at least two mirrors aligned so that absent optical losses light remains trapped between the mirrors. (Strictly speaking, this is true only for stable resonators, as noted below). The spatial distribution of light within the resonator is described mathematically by Gaussian eigenmodes ("modes"). Resonator types and resonator modes are important concepts for producing efficient diode-pumped laser operation and will be discussed throughout this book. These concepts are presented in more detail below.

As an optical amplifier is composed of an active gain element without a resonator, one can also consider a resonator without a gain element. Fabry-Pérot interferometers are examples of the latter. The point of this discussion, however, is that it is not possible to produce a laser without an active gain element located within a properly aligned resonator.

2.2 Resonators

Laser resonators are open structures containing two or more mirrors that are aligned to produce optical feedback to the gain element. In the simplest case, a resonator consists of two aligned mirrors. These mirrors are called end mirrors and define the optical cavity. Optical radiation circulates within the cavity, bouncing back and forth between the end mirrors and passing through the gain element.

Resonators can be stable or unstable. Stability is determined by the radii of curvature of the mirrors, the spacing between the mirrors, and the refractive index of the material in the recirculating path. In a stable resonator the lowest-order modes remain close to the optical axis, and diffraction losses are small. Stimulated emission takes place only within a relatively slender volume in the gain element. Higher-order modes are required to extract all of the available power from the pumped volume when the pump light fills the rod. This is often the case with lamp-pumped solid state lasers. Other features of stable resonators will be described in the sections that follow. Unstable resonators, on the other hand, have mode volumes that are typically much larger. These resonators are characterized by large diffraction losses, and, in fact, the diffraction spread past one of the end mirrors may be used as an output coupling mechanism. Unstable resonators are particularly useful for high gain media such as certain gas or dye lasers, but stable resonators are more practical for diode-pumped lasers. As will be shown, the small volume for the lowest-order mode in a stable resonator is an important advantage for diode pumping, allowing the production of high-efficiency laser output with excellent transverse mode control. Therefore, in this book we will discuss only stable resonators.

There are numerous types of resonators that are commonly used to produce laser emission. Two that are frequently used for diode pumping are the hemispherical—or, more accurately, "nearly hemispherical"—resonator and the confocal resonator. The first type of resonator is composed of one flat and one concave mirror separated by the radius of curvature of the curved mirror. This resonator is illustrated in Fig.

2.1. The confocal resonator is composed of two curved mirrors. For the symmetric confocal resonator both mirrors have identical radii of curvature and the separation is equal to the mirror radius. This resonator is illustrated in Fig. 2.2.

2.3 Laser resonator transverse modes

The distribution of light confined within an optical resonator is described by spatial patterns called transverse modes. Transverse modes are eigenmodes of the resonator. The Fresnel-Kirchoff formulation of Huygen's principle can be used to derive the integral equation that relates the fields at the two opposing mirrors of the cavity. Resonator modes are sets of transverse patterns that have the following property: after one round trip through the resonator, the exact pattern returns to the same location. These self-reproducing sets of intensity patterns represent the transverse modes of the resonator. The modes are approximately plane waves multiplied by the

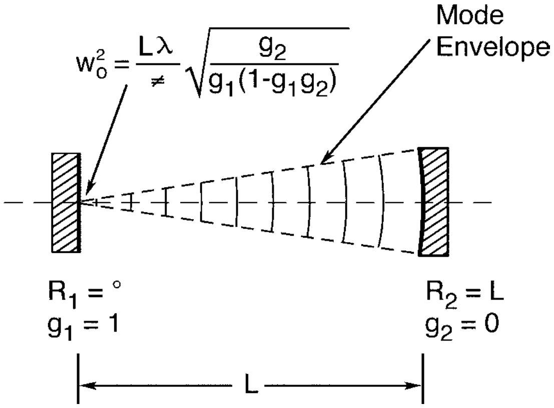

Figure 2.1. Hemispherical resonator.

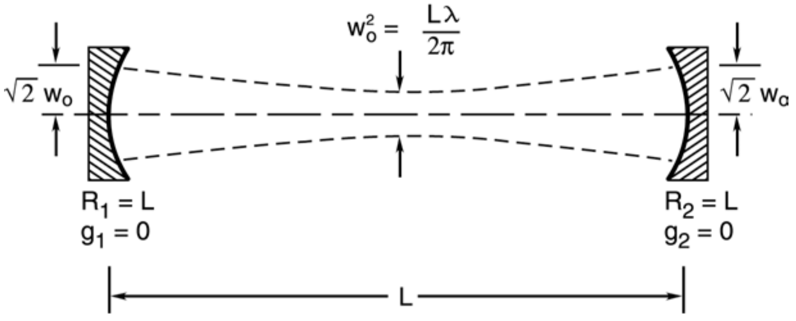

Figure 2.2. Symmetric confocal resonator.

transverse amplitude and phase profiles for the given eigenmode. These modes are referred to as TEM_{nm} for transverse electric and magnetic, and they are determined by the mathematical solution to the eigenequation for the resonator.

The transverse mode patterns will in general have a different field pattern at each transverse plane within the resonator. Therefore, the shape of the mode changes as it propagates along the resonator axis. The intensity profile of the transverse patterns is Gaussian, and the transverse modes are sometimes referred to as Hermite-Gaussian modes. The *n* and *m* subscripts in the TEM_{nm} mode designator refer to the number of intensity nodes of the resonator mode pattern along the x and y axis, respectively. That is, in rectangular coordinates, the x and y axes are orthogonal to each other and to the resonator propagation, or z, axis. Several mode patterns are illustrated in Fig. 2.3.

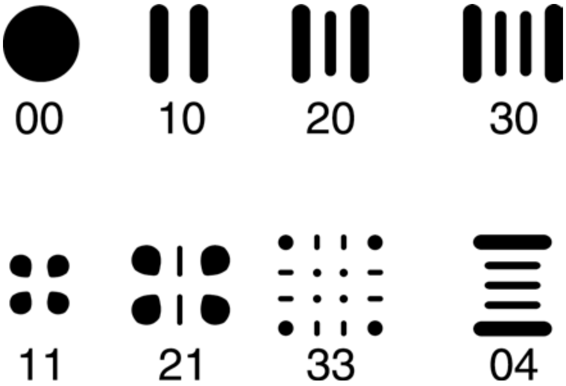

Figure 2.3. Transverse Gaussian mode patterns with *n, m* indicated.

2.3.1 TEM_{00}

The TEM_{00} mode is the lowest-order transverse mode. It has the lowest threshold, smallest beam waist and divergence, and contains no nodes in the output beam transverse intensity distribution. In discussing laser beam parameters such as mode waist and divergence throughout this text, it is implicit that the laser is operating in the TEM_{00} mode. There are several resonator mode parameters that are useful for discussing modes in general, and these are shown in Fig. 2.4. One important parameter is the mode waist w_0, which refers to the minimum cross-sectional beam radius within the laser resonator. The cross-sectional beam radii or "spot sizes" at the two end mirrors are labeled w_1 and w_2, respectively. The location of the waist relative to each mirror is designated as z_1 and z_2, respectively, while the separation of the mirrors is labeled *L*.

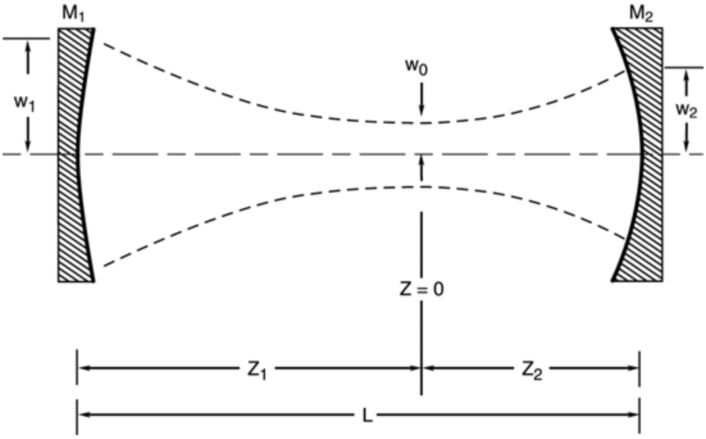

Figure 2.4. Notation for a two-mirror cavity.

The larger the spot sizes w_1 and w_2 relative to the mirror diameter, the larger the diffraction loss. For the exactly hemispherical resonator the spot size is infinite at the curved mirror and the waist vanishes at the flat mirror. The infinite spot size at the curved mirror makes the resonator unworkable. Therefore, in practice, the separation between the two mirrors is shortened slightly to produce a "nearly hemispherical" resonator. In this resonator the spot sizes at both mirrors are finite, and the beam waist remains at the flat mirror. The waist and spot size at the flat and curved mirrors are determined by

$$w_0^2 = w_1^2 = \frac{L\lambda}{\pi}\sqrt{\frac{g_2}{g_1(1-g_1g_2)}} \tag{2.1}$$

and

$$w_2^2 = \frac{L\lambda}{\pi}\sqrt{\frac{g_1}{g_2(1-g_1g_2)}}, \tag{2.2}$$

respectively, where

$$g_1 = 1 - L/R_1 \text{ and } g_2 = 1 - L/R_2 \tag{2.3}$$

and R_1 and R_2 are the radii of curvature of the flat and concave mirrors, respectively.

For the symmetric confocal resonator, the beam waist is located midway between the two mirrors. The waist and beam spot sizes at the two mirrors are

$$w_0^2 = L\lambda/2\pi \tag{2.4a}$$

and

$$w_1^2 = w_2^2 = 2w_0^2. \tag{2.4b}$$

Why do we care about the resonator mode size and location? This information specifies the volume within the gain element from which energy is extracted ("active volume"). Pump light deposited outside the mode volume is wasted. In some cases, putting too much excitation outside the boundaries determined by the lowest order or fundamental mode (TEM_{00}) can provide higher-order transverse mode operation in the laser. In order to produce an efficient TEM_{00} diode-pumped laser, it is important to tailor the pump energy deposition profile to fit within the active volume.

2.3.2 Multimode operation

Higher-order modes are less efficient and have a higher threshold, but will oscillate nonetheless if care is not taken in the resonator and pump optics design. Misalignment of the end mirrors can produce a single, higher-order transverse mode. However, in cases where too much pump energy is deposited in a relatively large volume, more than one transverse mode oscillates simultaneously. This is termed multimode operation and is routinely produced in many commercial lamp-pumped high-power lasers. The output beam characteristics in multimode operation, such as the divergence, focused spot size, Rayleigh range, etc., are poorly characterized. On the other hand, multimode operation can produce high laser output power in a side-pumped geometry, and for that reason it is common for lamp-pumped lasers.

2.3.3 Advantages of single transverse mode operation

TEM_{00} mode operation has numerous advantages that make it a desirable design goal. For example, the beam divergence is low, which provides high power density over large propagation distances. The focused spot size is smaller than that produced by higher-order modes and contains no nodes, making this type of beam useful for laser drilling, medical treatment, and other applications that require high brightness and small spot sizes. In addition, because the output beam intensity is characterized by a uniform Gaussian profile, it is useful for many illumination and imaging applications.

TEM_{00} operation is a particularly important consideration for efficient diode pumping. The resonator mode waist is the smallest of all transverse modes, therefore providing the opportunity for an excellent match to the tightly focused pump beam in an end-pumped geometry. The mode volume is small as well, so that for either side pumping or end pumping the diode pump flux can be concentrated within the laser resonator mode to produce high pump power density. This allows high gain to be developed within the resonator, and produces high pump optical-to-laser output efficiencies.

2.3.4 Longitudinal modes

Standing-wave resonators exhibit interference, and as a consequence, laser resonators support only specific optical frequencies. The separation $\Delta\nu$ between adjacent frequencies is given by

$$\Delta\nu = c/2n_i L, \tag{2.5}$$

where n_{i} is the average refractive index along the optical path within the laser cavity. When a laser produces output at only one of the supported optical frequencies, it is said to be operating "single frequency." There are many interesting applications for single-frequency laser operation, and two types of single-frequency lasers will be discussed in this book. One is the single-mode laser diode, which generates a single transverse as well as single longitudinal mode. These diodes are useful for certain types of end pumping and are discussed below. The other is a diode-pumped single-frequency laser. These lasers have many applications, including laser gyros and production of efficient nonlinear optical conversion, which will be discussed in more detail in Part III of this book.

When referring to longitudinal modes, the transverse mode designator includes a third subscript "q" and is written as TEM_{mnq}. These subscripts describe the transverse intensity and phase properties of the resonator mode (m, n) as well as the mode optical frequency (q). The optical frequency depends on the value of m and n as well as q, and is given by

$$f_{mnq} = \left[q + (m + n + 1) \frac{\cos^{-1}\sqrt{g_1 g_2}}{\pi} \right] \frac{c}{2n_{\mathrm{i}} L}, \tag{2.6}$$

where the factor g_n is given by

$$g_n = 1 - L/R_n, \tag{2.7}$$

and R_n is the radius of curvature of the n^{th} end mirror.

2.4 Laser diodes for pumping solid state lasers

Modern laser diodes are manufactured with a wide variety of architectures, packages, and power levels. We will limit the discussion of laser diodes in this book to those that are used for optical pumping. In this section we will consider only AlGaAs laser diodes, as other semiconductor lasers will be discussed in Part III.

AlGaAs diodes can be designed to emit at a wavelength in the range of approximately 725 nm to 850 nm. The emission wavelength is determined by the ratio of Al to Ga in the active region. The higher the Al concentration, the shorter the output wavelength. Since the market for high-power lasers is driven by pumping Nd-doped materials, the vast majority of diodes sold for laser pumping produce emission in the 808- to 810-nm range.

A heterojunction diode is shown schematically in Fig. 2.5. Semiconductor lasers operate by passing current through a p-n junction. Electrons traveling in the n region must have more energy than those traveling in the p region. Therefore, when the electron from the n region passes into the p region, it has excess energy. This excess energy is lost by photon emission. Light-emitting diodes (LEDs) operate on this same principle. The feature that distinguishes laser diodes from LEDs is that the density of energetic electrons located in the p region is sufficient to produce stimulated emission. As in a traditional laser, the gain medium is contained within a laser resonator. However, in the case of laser diodes, the resonator mirrors are the end faces of the semiconductor chip itself.

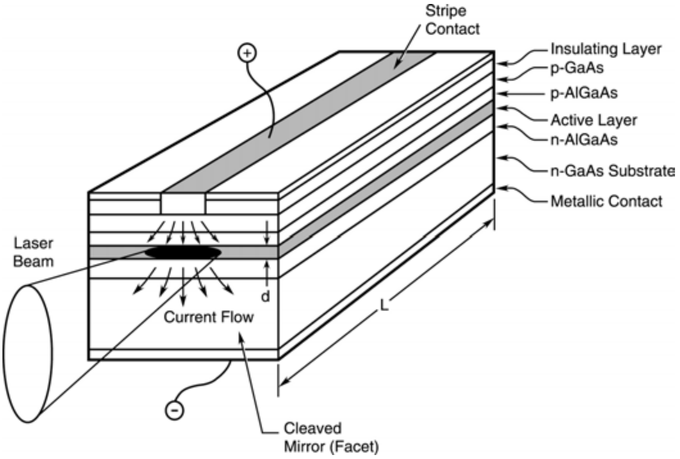

Figure 2.5. Schematic of a gain-guided heterojunction laser.

Several terms that are used to discuss the various features of laser diodes are worth reviewing. Referring to Fig. 2.5, the region of the structure that produces the gain is called the "active layer" or "active region." The Al content in this layer determines the output wavelength, and as shown, light emitted from the laser is produced in this layer. The laser resonator is composed of two flat end mirrors. These mirrors are formed by cleaving the end faces (called "facets") of the semiconductor device. The faces may be coated to produce a desired reflectivity, or may be provided with a "passivation" coating to protect the facets from damage or contamination by trace pollutants in the air. The high refractive index of AlGaAs produces 30% reflectivity per (uncoated) facet, generating sufficient feedback for efficient laser diode output. Since a laser diode emits light through both facets, high-power diodes are typically coated HR (highly reflective) on the rear facet. The electrical current that flows to the junction enters the device at a "stripe" contact. This contact runs the entire length of the diode, and individual diodes, whether discrete or one of many contained in a diode array, are referred to as single-stripe diodes.

2.4.1 Single-stripe diodes

Most high-power diodes are "gain guided," which means that horizontal confinement of the light flux propagating through the active region is accomplished by the small refractive index variation produced by the current-generated population inversion. If the light spreads in the horizontal plane outside of the horizontal dimensions of the stripe or “stripe width” (typically between 1 μm and 200 μm), it will be absorbed by the unexcited region of the active layer. In the vertical direction the lower refractive indices of the surrounding n and p layers (“cladding layers”) reflect light from the interface back into the active region. Since the horizontal waveguiding produced by the gain is a function of the excitation current levels, poor mode control results from these types of devices. Index-guided laser diodes have structural components incorporated into the architecture to confine light in the horizontal plane. These devices produce beams with much higher beam quality, but are typically limited in power to only a few hundred milliwatts.

2.4.2 Single-mode diodes

Single-mode diodes produce output in a single longitudinal as well as transverse mode. The highest power produced by a commercial single-mode AlGaAs diode is 200 mW. The advantage of the single-mode diode for laser pumping is that an extremely small focused pump spot size can be obtained. The spatial properties of the diode output beam are excellent as well. Furthermore, the output wavelength of the single-mode laser can be tuned (over several nanometers) to match the center of an absorption line in the solid state laser crystal. This allows high-density pump power deposition. Wavelength tuning is accomplished by changing the junction temperature; the laser output wavelength increases at the rate of +0.3 nm/°C. Temperature tuning to the absorption peak combined with the high beam quality produces low-threshold, high-slope-efficiency laser operation. Single-mode diodes cost significantly more per watt but are useful for pumping compact, low-power lasers.

2.4.3 Pulsed and cw diode operation

Individual laser diodes are inherently cw devices. Under qcw operation, the steady-state diode output characteristics are essentially cw and the peak output power produced by a single-stripe diode is limited to the maximum cw output power. For high-power linear or two-dimensional diode arrays, the cooling efficiency determines the maximum device duty factor. The duty factor represents the percentage of laser diode “on time.” For example, a linear array with a 20% duty factor indicates that the pulse width cannot exceed 20% of the inverse of the pulse repetition frequency. This would limit such an array producing 100-μs pulses to a repetition rate of 2 kHz.

Heat generated in the p-n junction must be removed rapidly to allow diode operation, with the heat load becoming more severe as the duty factor increases. Due to the low thermal conductivity of the semiconductor substrate, even the most advanced diode package designs have a limited cooling capacity. This limits the packing density of stripes on a cw array to about one-half the packing density of a low-duty-factor qcw array.