3

LASERS

INTRODUCTION AND SYNOPSIS

Laser action has been demonstrated in the laboratory in hundreds of materials – some of the more surprising being whisky, jelly and Chinese tea. In 1996, the Hubble space telescope discovered a gas cloud that acts as a natural ultraviolet laser near the huge, unstable star Eta Carinae. In total, over 15 000 energy transitions that result in the production of laser light have been reported. However, commercial lasers make use of about 40 active media: many are too expensive to be commercially viable; the efficiency of light production is often very low; or it might not be possible to construct a unit for practical reasons.

One feature that all lasers share is the unique nature of the light that they produce – a coherent, monochromatic beam of low divergence and high brightness. These properties form the basis of applications in fields as diverse as measurement, holography, data storage and communications. Material processing makes use of the *thermal* and *athermal* effects associated with the interaction of a laser beam with various engineering materials.

This chapter concentrates on lasers used for material processing. The principles of laser light generation from transitions between energy levels in active media comprising gases, solids and liquids are explained. Practical means of exciting media to achieve stimulated emission of light are described. The conditions for amplification of light in different types of resonator are considered. The nature of laser output from various combinations of active media, excitation methods and resonators is interpreted. These principles are then applied to commercial lasers for processing engineering materials. Further information on the output from individual lasers can be found in Appendix B and in the reading lists at the end of the chapter.

GENERATION OF LASER LIGHT

After Hertz had generated electromagnetic waves using a high voltage induction coil (Chapter 2), it was realized that radiation could be produced over a continuous range – the electromagnetic spectrum – shown in Fig. 3.1.

The spectrum may be divided into portions. Radio waves occupy the low frequency, low energy, long wavelength range, and are produced by antennae. Microwaves are generated by electrical oscillators. Infrared radiation originates from electronic transitions and molecular vibrations in materials. Visible light (radiation in the wavelength range 390–780 nm) is characterized in order of increasing wavelength as violet (390–430 nm), indigo (430–455 nm), blue (455–492 nm), green (492–577 nm), yellow (577–597 nm), orange (597–622 nm), and red (622–780 nm), and is produced from transitions between energy levels in the valence electrons of atoms. Ultraviolet light is emitted from corresponding high energy electronic transitions. *X*-rays result from deep electronic transitions. High frequency, high

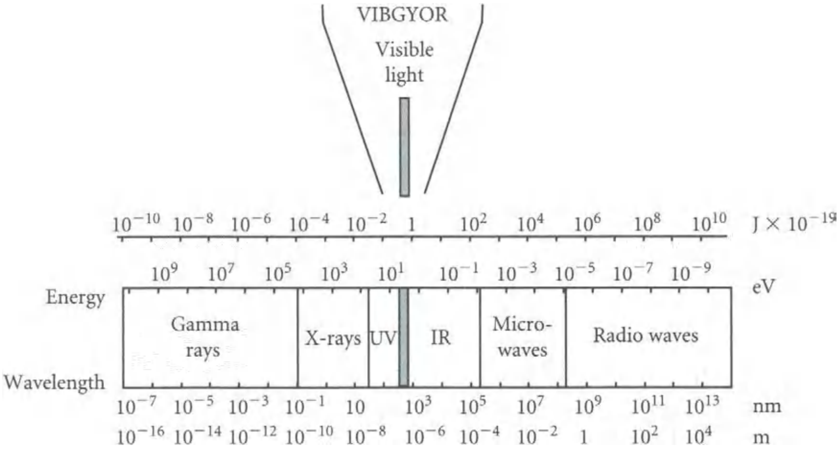

Figure 3.1 The electromagnetic spectrum: UV – ultraviolet; IR – infrared

energy, short wavelength gamma rays are produced by radioactive decay. In material processing applications, we are mainly interested in the infrared, visible and ultraviolet portions of the electromagnetic spectrum.

Laser light is generated by transitions between high and low states of energy in species (atoms, ions and molecules) in various media. Sustainable light generation depends on a suitable combination of fundamental physical phenomena to generate the light and an appropriate mechanical design to maintain and amplify the emission. We consider the fundamentals of laser light generation first.

ENERGY LEVELS

Atoms, ions and molecules, collectively known as species, exist in states characterized by discrete energy levels, also referred to as states.

The simplest forms of energy levels are those available in an isolated atom, such as hydrogen. The rules of quantum mechanics state that all particles have discrete energy states, which relate to different periodic motions of the constituent nuclei and electrons. The lowest possible energy level is the ground state, while other states are termed excited states.

When molecules in gases, liquids and solids are considered, the energy levels are no longer those of the individual atoms. Interactions with neighbours result in modifications to the energy levels. In condensed materials (liquids and solids), the atoms are packed together and the interactions are strong. The energy levels of the individual atoms then broaden and merge into an almost continuous band of closely spaced states.

In addition to electronic energy levels, molecules with more than one atom can possess quantized vibrational or rotational energy levels. Simple molecules such as nitrogen have only one vibrational mode. Complex molecules normally have many vibrational modes, all of which can interact. The carbon dioxide molecule, for example, can be visualized as a linear arrangement of two oxygen atoms and a carbon atom, with the carbon atom in the centre. The vibrational energy levels correspond to the motion of the oxygen atoms relative to the carbon atom. Vibrational transitions involve energy changes of about 0.1 eV – around an order of magnitude lower than the electronic transitions that produce visible light – and so such radiation normally lies in the mid-infrared region shown in Fig. 3.1. Rotational energy levels correspond to rotational motion of asymmetrical molecules, since angular momentum is quantized. These transitions involve energy changes around an order of magnitude smaller than vibrational transitions, and so are associated with far infrared radiation.

In addition to the values of the energy levels, the *lifetime* spent in those levels affects the temporal nature of radiation. The lifetime of a state depends upon the ease with which the state can be depopulated. States that exist for time scales on the order of microseconds and milliseconds, which are long in terms of laser transitions, are known as *metastable states*, and are important means of storing energy in laser systems.

Energy Level Notations

An atom can be identified as a positively charged nucleus surrounded by negatively charged electrons that are arranged in quantum shells. Each shell is described by using a *principal quantum number*, n. The shell is able to hold a certain number of electrons, given by $2n^2$. Thus the lowest energy quantum shell ($n = 1$) can hold 2 electrons. Successive quantum shells of higher energy hold greater numbers of electrons: 8 ($n = 2$), 18 ($n = 3$), 32 ($n = 4$) …. Electrons in a given shell have a similar energy, but no two are identical. Subshells, or *orbitals*, differentiate the probability that pairs of electrons occupy a given orbit relative to the nucleus. Electrons in a pair have identical energy, but opposite magnetic spin (the Pauli exclusion principle). The *azimuthal quantum number*, l, denotes states *s*, *p*, *d* and *f*, which have values of l of 0, 1, 2 and 3, respectively. The first quantum shell ($n = 1$) can contain only two electrons, both of which occupy the *s* orbital, which has a spherical probability distribution around the nucleus. The second quantum shell ($n = 2$) can contain eight electrons; two in the *s* orbital, and six in the *p* orbital, which has a slightly higher energy. The *p* orbitals have probability distributions shaped like dumbbells aligned with orthogonal axes. The third quantum shell ($n = 3$) can contain 18 electrons; two in the *s* orbital, six in the *p* orbital, and 10 in the higher energy *d* orbital. The fourth and fifth shells contain *f* orbitals, which can accommodate up to 14 electrons. The total number of electrons is equal to the atomic number of the element.

The Paschen notation describes the electrons in terms of particular shells and orbitals. The electrons in oxygen, of atomic number eight, are denoted $1s^2 2s^2 2p^4$; two electrons in the *s* orbital of the first shell, two electrons in the *s* orbital of the second shell, and four electrons in the *p* orbital of the second shell. As the number of shells and orbitals increases, the difference in energy between orbitals decreases, and some overlap in energy occurs; the inner orbital of an outer shell may have a lower energy than an outer orbital of an inner shell. The 26 electrons in iron, for example, are denoted $1s^2 2s^2 2p^6 3s^2 3p^6 3d^6 4s^2$. Electrons occupy the 4s subshell before the 3d subshell is filled. Transitions between adjacent states of angular momentum are denoted by lines in series: the *sharp* series lines denote transitions from *p* to higher *s* states; the *principal* series *s* to higher *p*; the *diffuse* series *p* to higher *d*; and the *fundamental* series *d* to higher *f*.

Energy levels involved in laser transitions are often named according to the *Russell–Saunders* convention. Each level is defined by an inner quantum number, J. Groups of related levels – *terms* – have multiplicities that are exclusively odd or even in a given spectrum. For terms of odd multiplicity the values of J are integers (0, 1, 2 …). Values of J for terms of even multiplicity are odd multiples of the fraction ½ (½, 1½, 2½ …). Terms are further defined by azimuthal quantum numbers, L, that have the values 0, 1, 2, 3, 4, 5, 6, 7 … for terms labelled S, P, D, F, G, H, I, K…, respectively (the hyperfine quantum number). A term of a given type and multiplicity comprises a finite number of energy levels whose inner quantum number is obtained by quantum theory. For example, an S term of multiplicity three has only one level with a value of J equal to 1 – it is designated $^3S_1$. A D term of multiplicity four comprises four levels whose values of J are 3½, 2½, 1½ and ½ – designated $^4D_{7/2}$, $^4D_{5/2}$, $^4D_{3/2}$ and $^4D_{1/2}$, respectively. The designation is augmented with two quantities: a prefix that distinguishes terms of the same type and multiplicity; and a superscript 'o' denoting that the configuration contains an odd number of *p*, *f*, *h*, etc. electrons. This notation is used in Appendix B to describe laser transitions.

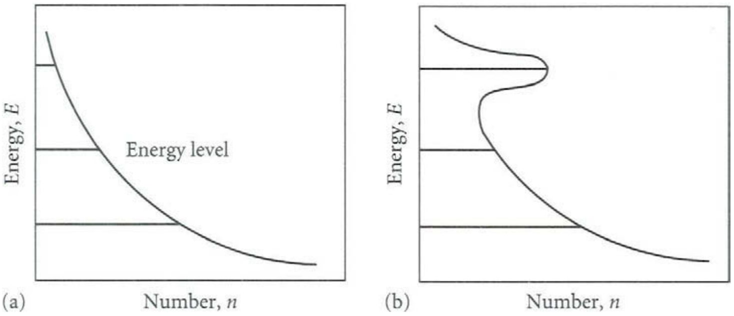

Figure 3.2 Distribution of energy in a species with (a) thermodynamic equilibrium and (b) a population inversion

Distribution of Energy

The normal distribution of energy in a population of species is given by the Maxwell–Boltzmann equation, illustrated in Fig. 3.2a. The ratio of the numbers N_1 and N_2, populating two energy levels, E_1 and E_2, respectively, is

$$\frac{N_2}{N_1} = \exp - (E_2 - E_1)/kT \tag{3.1}$$

where k is Boltzmann's constant (1.381×10^{-23} J K^{-1}) and T is the absolute temperature. At a given temperature, the number of species occupying higher energy levels decreases monotonically. As the temperature is increased, the number of species occupying higher energy levels increases, but the form of the distribution remains the same; the population of a lower level exceeds that of a higher level to give a condition of thermodynamic equilibrium. There is no driving force for energy to be released from the system, only for it to be redistributed internally.

Population Inversion

Normal populations occur naturally. However, a distribution can be disturbed artificially, such that the number of species occupying a higher energy level exceeds that of a lower level, Fig. 3.2b. This may be achieved by exciting or 'pumping' the population by using an external energy source. A population inversion is thus created – a prerequisite for laser light generation. A driving force now exists for energy to be released from the system; in the case of a laser, this energy is released in the form of light. Note the contrast between creating a population inversion and the effect of merely raising the temperature of the system; in the latter case the Maxwell–Boltzmann distribution is maintained, and so a driving force for the release of energy is not created.

EXCITATION

A population inversion may be achieved by using a variety of energy sources to excite the species. Electrical, optical and chemical sources are the most common in industrial lasers. Gaseous species absorb radiation over discrete ranges of wavelength (lines), and so electrical excitation, which produces energy over a relatively broad range, is common in gas lasers. Solids are not easily excited electrically, but optical pumping can be highly efficient in solid-state lasers. Chemical methods are generally more difficult to control, but are effective sources of excitation in chemical lasers.

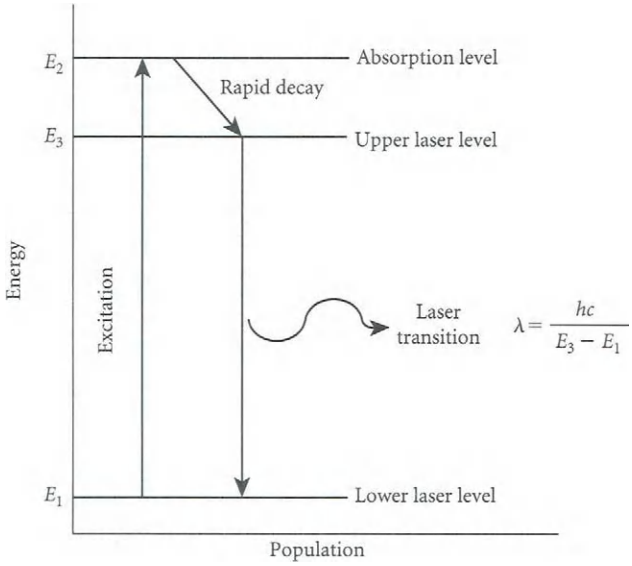

Figure 3.3 Energy transitions in a three-level laser system

In order to create a population inversion efficiently, it is necessary for the species to possess a large group of upper absorption energy levels, so that energy can be absorbed over an appreciable frequency range. These rapidly and efficiently feed more stable lower energy levels, which are termed the *upper laser levels*, or states. Below these lie the *lower laser states*. Laser light generation involves transitions from the upper to the lower laser states. In order to maintain a population inversion, the lifetime of the lower laser state must be shorter than that of the upper state. In addition, the *rate* of population of the upper state must be greater than that of the lower state.

Energy Level Transitions

Einstein proposed that light consists of bundles of wave energy, termed photons. It was originally thought that photons and species may interact only by absorption of a photon (with a corresponding increase in energy), or spontaneous emission of a photon originally in a higher energy state (leading to a reduction in energy). (Energy can also be reduced without the emission of a photon; a process known as non-radiative decay.) However, Einstein concluded that there must exist a third mechanism of interaction – induced or stimulated emission – in which an excited species could be stimulated to emit a photon by interaction with another photon. This is the basis of light amplification by stimulated emission of radiation, from which the acronym laser is formed.

The simplest form of laser is based on transitions between two energy levels, E_2 and E_1, which represent the ground and excited states. The ammonia maser and diode laser are examples of two-level systems. However, it is difficult to obtain useful light amplification in this type of system because as species in the upper laser level emit radiation their number approaches that of the species in the ground state, and absorption falls towards zero. For this reason, industrial lasers are often based on three and four energy level systems.

In a three-level laser system, illustrated in Fig. 3.3, excitation is achieved by pumping to the E_2 absorption level, or levels. If an energy level E_3 exists, which lies slightly below E_2, rapid non-radiative decay can occur to the level E_3 with little loss of energy. E_3 becomes the upper laser level. Laser emission

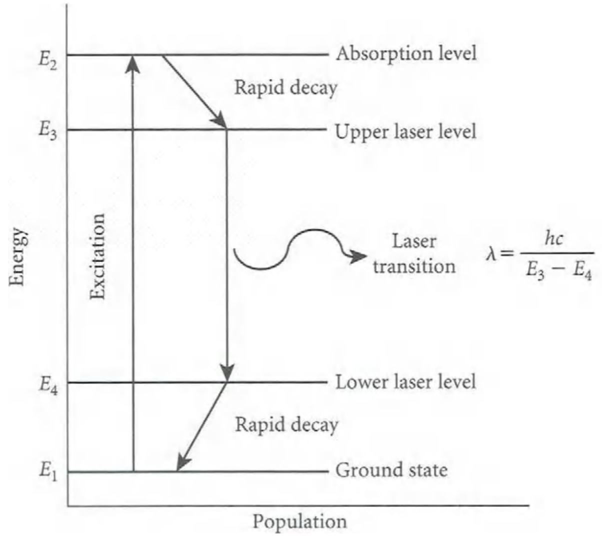

Figure 3.4 Energy transitions in a four-level laser system

then takes place between the levels E_3 and E_1. A number of conditions must be fulfilled for this type of laser to operate. First, the energy required for excitation must be relatively high, because more than half of the entire population of the species must be raised out of the ground state (which may be the lower laser level). Second, the transition $E_3 \rightarrow E_1$ must be very probable. Third, the species must be able to remain in the E_3 state longer than the E_1 state in order to build up and maintain a population inversion. If the lower laser level in a three-level system is the ground state, a population inversion is more difficult to achieve, and output is limited to pulsed operation.

A population inversion can be generated more easily if the laser transition terminates in a state that is not the ground state. This is the case for a four-level system, illustrated in Fig. 3.4. Species are excited to the level E_2, followed by rapid non-radiative decay to a lower level, E_3. The laser transition occurs between levels E_3 and a second intermediate level, E_4. Rapid relaxation to the ground state, E_1, is then desirable for efficient operation. The potential for four-level operation is much higher than three-level operation because the threshold pump energy is considerably lower; it is not necessary to invert the entire population. Since the laser transition is to an intermediate level which is normally unpopulated, a four-level laser can operate in continuous wave mode.

LIGHT AMPLIFICATION

We have seen how light may be generated by stimulated emission of photons. However, a laser works on the principle of light amplification by stimulated emission. Amplification can only occur if emission takes place in a suitable device – the optical cavity. Amplification is achieved when stimulated emission increases the number of photons circulating in the optical cavity, illustrated schematically in Fig. 3.5.

The amplification achieved is the gain of the system. If the circulating power in a laser is restored to its original value after a round trip in the optical cavity, then the round trip gain is equal to the round trip loss; this is known as the *threshold* gain. If the loss is greater than the gain then the laser will not produce light. Positive gain is the second requirement for laser light generation – the first being a population inversion.

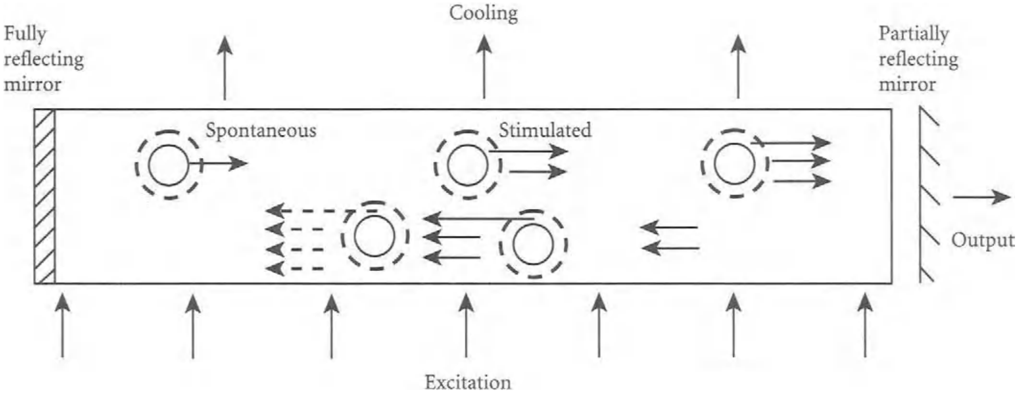

Figure 3.5 Schematic illustration of amplification by stimulated emission of radiation

There are two types of gain: saturated and unsaturated. Unsaturated gain, often referred to as small-signal gain, occurs with small input values. In contrast, with high excitation the number of photons passing through the optical cavity significantly depletes the population inversion, and the gain is reduced, or saturated. The gain is independent of the excitation power. It is the circulating power, and hence the output power, which increases with increasing excitation power.

OUTPUT

In a light bulb, electrons in the atoms and molecules of the filament are pumped to higher levels by electrical excitation. Electrons fall randomly to lower levels independently of one another, emitting light with a random collection of wavelengths (colours). Since many electrons are constantly falling to different levels, a range of wavelengths is produced, and the net result is the production of white light. The light that is produced is emitted in random directions.

In contrast, in the process of *stimulated emission*, a photon collides with another excited species, causing it to release its photon prematurely. Photons travel in the same direction until the next collision, thereby building a stream of increasing density, Fig. 3.5. Photons have the same phase (temporal and spatial properties), frequency and polarization. Laser light is therefore *coherent* and *monochromatic*, and has *low divergence* and *high brightness*.

Laser light can take the form of a continuous wave (CW), a pulse, or a train of pulses. The length of the pulse can vary from a tenth of a second to a few femtoseconds (10^{-15} s). Pulses may be produced at a rate of between one and several thousand per second. The average power may vary between milliwatt and kilowatt levels, with peak power attaining the order of gigawatts. Some lasers can be tuned to produce a range of wavelengths.

Efficiency

A number of efficiency values can be defined when considering laser light generation. The *fluorescent quantum efficiency*, η_f, is the ratio of the number of species participating in the laser transition to the number of species raised from the ground state. (Species in the excited state may decay to states other than the upper lasing state, and atoms in the upper lasing state may decay to states other than the lower lasing state.) The *thermodynamic efficiency*, η_t, is the ratio of the amplification energy to the energy required for excitation. Since laser photons have less energy than the excitation source, the thermodynamic efficiency lies below 1. An overall wall plug efficiency, η_w, can also be defined:

$$\eta_w = \eta_e \cdot \eta_T. \tag{3.2}$$

Typical wall plug efficiencies for material processing lasers can be found in Table B.1 (Appendix B).

CONSTRUCTION AND OPERATION OF COMMERCIAL LASERS

So far we have considered the theoretical aspect of laser light generation. Now we examine means of constructing and operating a practical laser.

A laser requires four basic components to operate: an active medium in which light can be amplified by stimulated emission of radiation; a means to excite the medium – the excitation or 'pumping' source – to maintain the population inversion; a means to provide optical feedback – the optical cavity; and an output device to enable usable amounts of beam energy to exit the laser.

Additionally, a laser requires power and control systems, means of cooling the active medium and an interface for operation.

Active Media

Industrial lasers are normally classified by the active medium, which may be a gas, an insulating solid, a semiconductor or a liquid.

Gases

Gases possess a number of properties that account for their popularity in industrial lasers: they can be excited directly with an electric current; they are homogeneous; they allow flexibility in the design of the resonator, which can be scaled easily; they can be manipulated aerodynamically, facilitating cooling; propagation of the beam is unimpeded; and they are relatively inexpensive. Laser emission from gases is well defined, and occurs in three discrete parts of the electromagnetic spectrum: ultraviolet, visible and infrared.

The noble gases neon, argon, krypton and xenon, and mixtures of helium and neon, are the active media in *neutral atom* gas lasers. Neutral atoms produce light in the range between mid-ultraviolet and near infrared. The energy levels for infrared emission lie close to the limit of atomic ionization. As a result, the atom is excited to a high energy level, which in turn means that the photon emitted has a relatively small amount of energy. The fluorescence quantum efficiency is therefore low in atomic gases. Not every excited species is able to produce laser light; the ratio of those that can to those that cannot varies as the cube of the wavelength, thus favouring the infrared end of the electromagnetic spectrum. However, both the emitted energy and the excitation working temperature vary approximately with the reciprocal of the wavelength. Neutral atom gas lasers therefore incorporate relatively weak discharges and have moderate gain and power output. They can be used for fine scale, low power precision material processing.

The excitation energy of an ion is larger than a neutral atom; ionized gas lasers therefore produce short wavelength light, in the range between mid-ultraviolet and visible. High current densities are required for excitation since energy is used to ionize the atom and then to excite it. These lasers consequently have high plasma temperatures, and require substantial cooling to operate. Ions of noble gases, notably argon and krypton are used in commercial designs, producing ultraviolet light that is suitable for fine-scale material processing.

Molecules produce relatively long wavelength light in the range between visible and far infrared. The relevant transitions are those between vibrational and rotational energy levels in the molecule. Two types are possible: transitions between vibrational states of the same electronic level, as in carbon dioxide; and transitions between vibrational states of different electronic states, as in nitrogen. The vibrational levels of the electronic ground state are close to the ground state of the molecule. The photon energy is therefore a significant fraction of the excitation energy, resulting in a relatively high value of quantum efficiency; almost all of the electrons present in the discharge participate in the excitation process. Diatomic molecules are less suitable for continuous laser emission because of the unfavourable lifetime of such molecules excited to vibrational levels of the electronic ground state. Two molecules are particularly good emitters: carbon monoxide (around 5 µm); and carbon dioxide (around 10 µm). Moderate current densities are involved, but the ability to use large volumes allows multikilowatt output power to be obtained, hence the development of high power lasers for material processing based on these media.

Transitions can also take place between electronic states in a metal vapour. There are three basic types of metal vapour laser: metal ion; recombination; and neutral atom. The helium–cadmium and helium–selenium lasers are well-developed examples of the metal ion type. Recombination lasers are still under development (strontium is being investigated). Of the neutral atom types, copper and gold vapour lasers are the most popular, although lasers based on lead, manganese and barium have been examined. Emission occurs via relatively high energy transitions between excited states and low lying ground states, which result in the production of visible or ultraviolet light.

The term *excimer* is derived from excited dimer, which refers to a diatomic molecule formed by a chemical reaction after one or both of its constituents have been excited. The term has come to be used to describe the association of two different atoms as well: a rare gas (neon, argon, krypton or xenon) and a halogen (fluorine, chlorine, bromine or iodine) – which strictly should be termed an exciplex (excited complex). The rare gas and the halogen are excited to form positive and negative ions, respectively, which are attracted and combine to form an excimer. An inert gas, normally helium or neon, regulates energy transfer. Since the molecule has dissociated, the ground state is empty, and a population inversion is readily formed. As the excimer loses its energy and returns to the ground state, it emits a photon of ultraviolet light, and the molecule dissociates into free atoms that are available to take part in the excitation process again. Transitions between both electronic and vibrational energy states result in emission. Since the lifetime of the excited state is on the order of nanoseconds, only pulsed output can be obtained.

Liquids

The active medium in most liquid lasers is a fluorescent organic dye dissolved in a solvent that flows through the laser. These dyes are large complex molecules, which have a large number of vibrational and rotational energy levels that blend together into energy bands. Emission has been obtained from about 50 dyes, providing a wide selection of lasing wavelengths. By combining several dyes, output wavelengths covering the visible spectrum may be produced. Their useable lifetimes range from hours to months, depending on the dye and the means of excitation. Liquid active media have advantages over gases and solids: they can be prepared more easily (solids require a high degree of optical homogeneity); and they contain a higher density of atoms than gases.

When the molecule drops from one broad electronic state to another, the wavelength of light emitted depends on the start and end points. The emission bandwidth can therefore be very broad – up to 180 nm in some dyes. The laser bandwidth can be selected by limiting the bandwidth of feedback provided by the resonator using prisms, gratings, birefringent filters, and other devices, thus enabling the output to be tuned.

Insulating Solids

The active media in solid state lasers (not including semiconductor lasers) comprise a host material doped with ions of transition or rare earth elements. (Colour centre, or F-centre lasers are a small group of laser-pumped sources with crystalline active media – including potassium chloride with lithium or sodium – that contain defects, which cause intense absorption, but are rarely used for material processing.) The term 'solid state' indicates that the active medium in the laser is a solid, rather than a gas or a liquid – it should not be confused with the terminology used in electronics. In comparison with gas lasers, solid state lasers require no mechanical devices for media circulation, complex heat exchangers, or vacuum and gas-supply systems. However, the thermal conductivity of the host determines the amount of heat generated, which limits the working range through thermal lensing. A beam of relatively high divergence is produced from solid active media because inhomogeneities in the active medium cannot be smoothed out, as in circulating gas lasers.

Suitable hosts are crystalline materials and glasses that are stable, hard and optically isotropic, and which possess sufficient tensile strength to be used in a variety of shapes. Materials are required to have a high thermal conductivity and low thermal expansion coefficient, for thermal stability, and must be able to accept dopant ions in substitutional sites. Yttrium aluminium garnet ($Y_3Al_5O_{12}$), referred to as YAG, sapphire (Al_2O_3), calcium fluoride (CaF_2), and silicate and phosphate glasses meet these criteria. YAG has a particularly good combination of low thermal expansion and high thermal conductivity, and is the host in the Nd:YAG laser – a popular solid state laser for material processing, available with output up to the multikilowatt level. Glasses can be doped to higher concentrations than YAG, with good uniformity, and can be produced in larger sizes with a greater variety of geometries. Glasses are particularly suitable for pulsed lasers.

The dopant contains an interior unfilled shell of electrons, which leads to a narrow emission bandwidth; this is favourable for laser operation since it leads to high gain and reduces the requirements on the population inversion necessary for operation.

The host material determines the characteristics of the available energy levels, and therefore the exact wavelength of light generated. When ions are embedded in a solid, they can absorb radiation over a much wider band of wavelengths. Laser transitions occur between low-lying energy levels, the spacing of which are determined by the forces acting on and between the electrons in partially filled electronic shells. There are three principal interactions to consider: coulomb forces acting between the electrons; crystal field interactions; and a coupling between electron spin and orbital angular momentum, known as spin-orbit coupling. Coulomb forces are normally the largest: they split the single electron configuration into a number of levels. In transition metals, the crystal field interactions are the next largest since the partially filled electronic shells are not shielded. This splits the basic energy levels into further levels. In the case of transition metals, the spin-orbit interaction is relatively small, and is not considered here. In rare earth ions, the spin-orbit interaction is stronger than the effects of the crystal field. The crystal field then acts to produce further splitting of the multiplets. The wavelength range of light produced by solid state lasers covers the visible and infrared, between about 300 and 3000 nm.

Solid active media enable relatively small lasers to be constructed, with no gas flow maintenance requirements. However, heating limits the power that can be generated and the beam quality is relatively poor at high power.

Semiconductors

In contrast to the single energy levels found in isolated atoms, electrons in semiconductors occupy broad bands of energy levels. Each band comprises a number of closely spaced levels, which originate from the superposition of all the energy levels of the atoms making up the solid. The equilibrium atomic separation results in a sequence of bands separated by energy gaps. The most important features for laser light generation are the uppermost occupied band, the first empty band, and the gap in between, which are termed the valence band, the conduction band, and the energy gap, respectively.

Electrons can be excited from the valence band to the conduction band. In this way electrical conduction can take place via the motion of electrons in both bands. The absence of an electron in a band can be considered as a 'hole' that has a positive charge. In a pure semiconductor material the number of electrons and holes are equal. The number can be changed by adjusting the temperature, or by doping the semiconductor with atoms whose valences differ from that of the host material. If tetravalent silicon is doped with pentavalent phosphorus, each phosphorus atom replaces one of the silicon atoms, and four of its five valence electrons are used to satisfy the bonding requirements of its four neighbours. The remaining electron is not used in bonding, and is only weakly bonded to the phosphorus atom, and so it is readily detached, and promoted to the conduction band. Such dopants are known as donors, and the material is known as *n*-type, where *n* denotes negative, referring to the electron density. Dopants that have a valence one less than the host – acceptors – can also be added to form *p*-type material (*p* denotes positive). Light is emitted when electrons drop from the conduction band and occupy, or recombine with, a hole in the valence band, to form a neutral atom in the crystal lattice. The energy of this transition determines the wavelength of the light generated. The high concentration of electronic states in the bands provides high gain.

A junction can be made by placing *n*- and *p*-type materials together. Since there are more electrons in the conduction band of the *n*-material than the *p*-material, electrons flow from the *n* to *p* conduction bands. Conversely, holes flow from the *p*- to the *n*-valence bands. The simplest junction comprises one *p*-doped and one *n*-doped layer of group III and group V compounds, such as gallium arsenide (GaAs). This is referred to as a homojunction laser, since it comprises layers of the same basic material.

For practical reasons, most semiconductor lasers are of the *heterojunction* type. Heterojunctions comprise several layers of different semiconductor materials, based mainly on gallium, aluminium and indium in compounds of arsenide, phosphide or antimonide. The optical cavity is limited to a narrower region around the *p*–*n* junction because of the difference in refractive index between the layers. Low current is therefore needed for excitation, and heat build-up is reduced. Most designs of diode laser are based on blocks of semiconductor that may be no more than 1 mm square and 100 µm in thickness. Techniques such as liquid phase epitaxy are used to grow the thin layers of semiconductor crystal used in commercial diode lasers. Semiconductors are combined in arrays to attain multikilowatt output for material processing.

Excitation

As mentioned above, a population inversion is achieved in the active media of industrial lasers by using electrical, optical and chemical means. (Electron beams were also used in the early days of laser development.)

Electrical Pumping

Direct current (DC) excitation is relatively compact, simple and cheap, and comprises a high voltage transformer and rectifier with a large smoothing capacitor. A glow discharge is created in a gaseous medium by electrons emitted at the cathode, which travel through the gas under the action of an electric field. Excitation is achieved through the collision of energetic electrons with gas atoms and molecules. Since the electrodes must be placed inside the resonator, impurities are formed from reactions with the gases, and the electrodes must be cleaned at regular intervals. The discharge can become unstable, and an arc now forms which allows thermal equilibrium to be achieved, preventing laser action.

Power generated by radio frequency (RF) excitation can be coupled capacitively through dielectric materials, such as quartz glass, into a gas mixture. The electrodes can therefore be mounted on the outside of discharge tubes. There is no electrode wear or contamination, which results in smaller discharge, lower gas consumption, and longer maintenance intervals. The discharge is also more homogeneous since the potential difference is distributed across the entire electrode surface. Capacitors can be used to limit the discharge current, rather than the ballast resistors of DC designs, thereby reducing resistive losses. Higher pulse frequencies and pulse modulation are possible, increasing the flexibility of operation. Since the separation of the electrodes is equal to the diameter of the tube, only a relatively low potential difference is required. However, an RF power source is more expensive than a DC source, and the resonator must be screened against emitted interference radiation. The power supply conversion efficiency is lower, resulting in higher electrical consumption than DC-excited lasers of similar output.

Alternating current (AC) excitation of pulsed gas lasers refers to frequencies in the range up to several hundred kHz. (Frequencies in the MHz range fall in the category of RF excitation.) AC excitation results in a rapidly changing electric field that promotes the conditions for maintenance of a glow discharge, allowing high electrical power densities to be produced and compact resonators to be constructed. The electrodes are mounted outside the discharge tubes, and so AC excitation enjoys similar benefits to RF excitation. The high spatial homogeneity of the discharge results in good beam quality and the wide stability range allows greater design freedom.

Optical Pumping

The difficulties associated with exciting insulating solids electrically mean that optical methods are preferred. The most common excitation sources are flashlamps, arc lamps and semiconductor lasers.

Flashlamps are glass or quartz tubes filled with a gas. Xenon is used when the output of the laser is on the order of watts. Krypton is more appropriate when a low current density discharge is needed, such as in continuous wave operation. Flashlamps provide a source of high intensity light, but a large part of the radiation is not absorbed by the active medium, and is wasted as heat. The pulse repetition rate of a flashlamp is generally below 200 Hz. Flashlamps normally last between 500 and 1000 hours in continuous use.

Arc lamps are favoured when continuous wave operation is required. The lamps are filled with xenon and krypton. A higher pumping energy is required for CW operation because of the lower photon flux in the laser. Lifetimes between 400 and 1500 hours are typical.

As the cost of semiconductor lasers decreases, the use of diodes as a means of optical excitation is increasing. Diodes emit light at a fixed wavelength, which can be chosen to match the absorption bands of the active medium, resulting in significantly higher pumping efficiency than flashlamps and arc lamps. Diodes may also be located in novel orientations with respect to the active medium to maximize pumping efficiency.

Chemical Pumping

The energy produced by a chemical reaction, normally in the gaseous or liquid states, is used as the excitation method in chemical lasers. The reaction is initiated and sustained by a plasma or flashlamp, often via a mechanism involving photodissociation. Energy is transferred efficiently to the active medium by resonance.

Optical Cavity

In order to sustain laser action in a practical device, it is necessary to enclose the excited medium in an optical cavity. This is a container bounded by two mirrors. The principal cavity parameters can be varied to optimize the output from a simple two-mirror optical cavity: the separation between the mirrors; the radii of curvature of the mirrors; and the reflectivities of the mirrors.

The simplest type of optical cavity is the Fabry–Perot interferometer – a container bounded by two parallel plane mirrors. Light travelling along the axis is reflected back and forth, the principal condition being that the spacing corresponds to an integral number of wavelengths. However, plane mirrors require exact alignment, and the reflective coating is critical in maintaining laser action. Spherical mirrors with a large radius of curvature are less sensitive to alignment, while still being able to fill the cavity, and are therefore commonly used in practical lasers.

The number of mirrors in the optical cavity is minimized to reduce losses that arise from imperfect reflection, and instabilities caused by temperature fluctuations. Cavities can be folded to lengthen the photon path, which increases power output while maintaining a small footprint, but the need for additional mirrors limits the number of folds in practical designs. Mirrors are normally made from water-cooled copper plated with silicon or gold, and have a large radius of curvature, typically tens of metres. The curvature of the mirrors determines the wavefronts that will oscillate in the cavity, and hence the modes of the beam that are supported.

Photons are repeatedly reflected through the active medium, which has two effects: the probability of stimulated emission is increased through an increase in the radiance flux of the photons; and feedback allows the emitted wave to grow coherently. Photons that do not travel parallel to the optical axis of the laser are quickly lost from the system; as a result the beam has low divergence. Reflections that are out of phase are lost through destructive interference, which maintains the coherence of the beam. Photons that do travel parallel to the axis have their path length considerably extended by optical feedback provided by the mirrors, before leaving the laser. This not only serves to amplify photon generation, but also produces a collimated beam of light. Losses in the cavity arise from a number of sources: transmission through the output coupler (the useful output); scattering by optical inhomogeneities in the active medium; absorption and scattering by the mirrors; diffraction around the perimeter of the mirrors; and absorption in the active medium by energy levels not involved in the laser transition.

The term *resonator* is used here to denote the combination of the optical cavity and the excitation device, together with the structure that holds and maintains the integrity of the optics. The resonator also includes devices that are inserted into the optical path to provide features such as pulsing capability, polarization control and mode control.

Stability of the Optical Cavity

The geometrical arrangement of the mirrors leads to the possibility of a large number of potential cavities capable of sustaining laser action. Cavities are classified as stable or unstable. A simple differentiation is that the beam converges in a stable cavity, whereas it diverges in an unstable cavity.

The main advantage of a stable cavity is that a fundamental mode (beam intensity distribution) can be generated that has standard measurable characteristics. High power, high order modes with a central intensity peak that are useful for material processing can be generated in a stable cavity. Rays of light are focused in a stable cavity. The mode remains constant as the beam propagates, or is focused. However, since the light rays pass through a waist between the mirrors, a stable cavity has a relatively small effective mode volume, which limits the power that can be generated. Examples of stable cavities are illustrated in Fig. 3.6.

A *confocal* cavity uses two spherical mirrors of equal radius, with coincident foci. This relaxes alignment tolerances somewhat, and reduces diffraction losses. A *spherical–flat* configuration is popular in high power lasers because of the relative ease of alignment and its good mode-filling characteristics. The radius of curvature of the focusing mirror is several times the cavity length. The beam can be extracted from a stable cavity by a partially reflecting transmissive window.

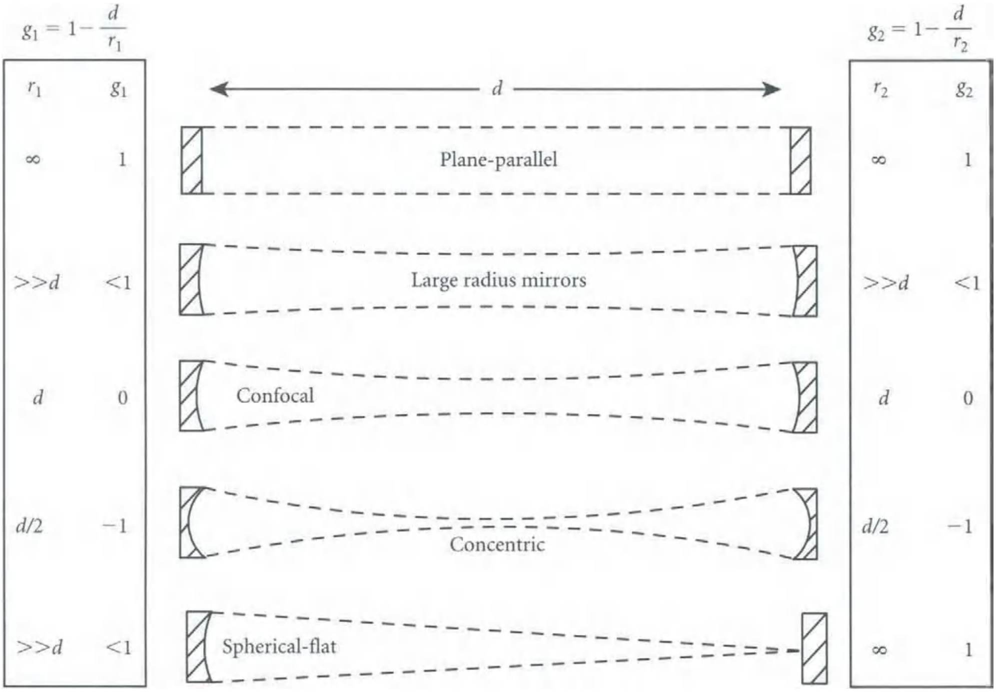

Figure 3.6 Stable optical cavities (*r* is the radius of curvature of a mirror and *g* is a geometrical factor used to characterize the stability of the cavity)

In an unstable optical cavity, radiation is not confined to a narrow beam, but is deformed so it is reflected between the cavity mirrors, filling the entire cross-section of at least one mirror. Rays of light diverge within the cavity. Examples of unstable cavities are illustrated in Fig. 3.7.

The most widely used unstable cavity design is the *positive branch confocal* cavity, which comprises a large concave mirror and a smaller convex mirror, around which the beam exits the cavity. The disadvantage with the *negative branch* design, which comprises two concave mirrors, is that the beam is brought to focus between the mirrors, reducing the active volume, and causing disruptive plasma generation. The diameter of the intensity distribution is determined by the internal apertures. The beam is normally extracted from an unstable cavity by using an annular scraper mirror. Unstable cavities are capable of producing a variety of beam intensity distributions, but the size of the resonator normally means that all but the lowest order distributions are eliminated. The intensity distribution in the output beam is annular when a scraper mirror is used. Unstable cavities have a number of advantages over stable designs: a single beam intensity distribution is possible even with a wide cavity; energy can be extracted from a large resonator volume in short resonators; and partially reflecting elements, which are expensive and sensitive to operating conditions, can be eliminated. The annular intensity distribution from an unstable resonator fills in at its centre as it propagates, or when it is focused. This can result in a near-Gaussian beam intensity distribution at the focus. Unstable cavity design is a compromise between power and beam quality.

As a general rule, a cavity is stable if the centre of curvature of one mirror, or the mirror itself, but not both, falls between the other mirror and its centre of curvature. In mathematical terms, a cavity is

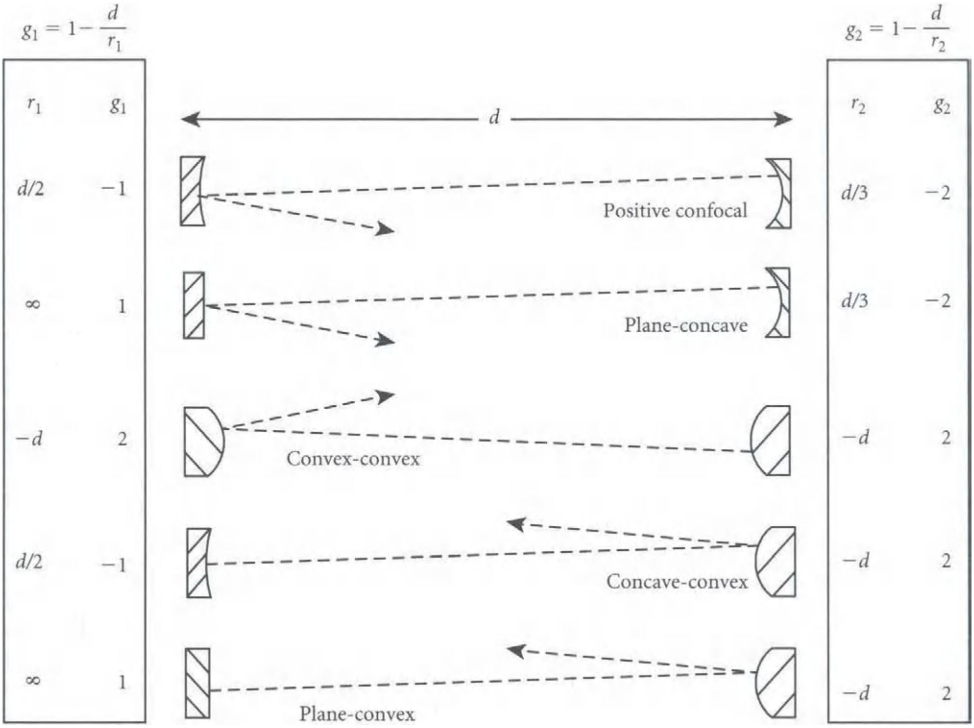

Figure 3.7 Unstable optical cavities (r is the radius of curvature of a mirror and g is a geometrical factor used to characterize the stability of the cavity)

stable if the following condition is met:

$$0 \leq \left[1 - \frac{d}{r_1}\right]\left[1 - \frac{d}{r_2}\right] \leq 1 \qquad (3.3)$$

where d is the distance between the mirrors and r_1 and r_2 are the radii of curvature of the mirrors. This can be written:

$$0 \leq g_1 g_2 \leq 1 \qquad (3.4)$$

where $g_i = 1 - d/r_i$. The conditions required for stability, and various cavity configurations are shown in Fig. 3.8. Note that stable cavity designs that lie close to the stability boundary may become unstable with slight changes, such as a variation in the mirror curvature caused by thermal expansion.

An etalon – a piece of glass fabricated such that the two surfaces are parallel – may be inserted in the optical cavity to ensure that it operates in a single mode. The etalon effectively operates like an internal Fabry–Perot interferometer.

Resonator Support

The optical cavity and other components of the resonator are supported by a structure designed to minimize relative movements, both linear and angular, which would result in instabilities in power output, beam mode and pointing. The structure is made from a material with a very low coefficient of thermal expansion, such as Invar, in order to minimize changes in cavity dimensions during operation.

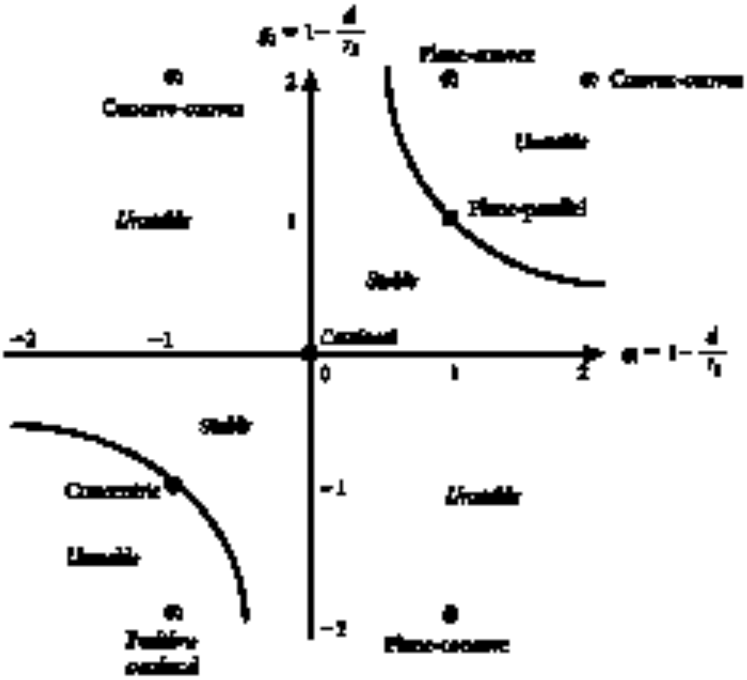

Figure 3.6 Conditions for stable and unstable cavities in terms of the spacing of the cavity optics, d, and the radii of curvature, r_1 and r_2

The resonator structure is also isolated from mechanical forces arising from dimensional changes and vibrations.

Output Devices

Light is extracted from the optical cavity through an output coupler. This is a 'window', which may be a partially transmitting solid, a fully transmitting gas, or a diffraction grating.

Transmissive solid output couplers are popular in relatively low power lasers since they can be made to be wavelength specific, transmitting a fraction of the cavity light within a limited range of frequency. The remainder is reflected back into the cavity. An antireflection coating, such as lead fluoride, is applied in order to achieve the desired reflectivity.

A scraper mirror is used to extract the beam from higher power unstable resonators. The beam is focused through an orifice across which an isolating curtain of high velocity, dry, compressed air flows – an aerodynamic window.

The broad emission spectrum of some lasers enables the output to be tuned if a diffraction grating is used for the output coupler.

OUTPUT

Earlier, we learned that laser light has four main characteristics that differentiate it from the light produced from, for example, an electrical light bulb: it is monochromatic, coherent, has low divergence and has high brightness.

Monochromatic light effectively has a single wavelength – light is emitted in a well-defined segment of the optical spectrum. In practice, an industrial laser operates in a very narrow band of wavelength around a central peak. Emission is said to occur on several lines within a narrow band. The monochromatic nature of laser light is the basis of applications such as measurement, alignment and holography.

The beam from the laser normally converges to a waist as it leaves the resonator, where its diameter is a minimum, after which it diverges along the beam path. The tendency for the beam diameter to expand away from the waist is a measure of the beam divergence. Low divergence is the property that enables a laser beam to retain high brightness over a long distance, and is the basis of alignment systems. (A beam of red light emitted from a laser situated on earth may be only about 1 kilometre wide when it reaches the moon, situated at a distance of 380 000 km.)

Coherent radiation comprises waves travelling with the same wavelength, amplitude and wavefront. It is a measure of the degree to which light waves are in phase in both time and space. Laser radiation has high coherence. Spatial coherence is a measure of the difference in the spatial position of waves. Coherent laser light is up to 100 000 times higher in intensity than incoherent light of equivalent power, since the divergence, or dispersion, of energy is very low as the beam propagates from the laser. Because light propagates with a finite velocity, a temporal coherence can be defined, which is a measure of the difference in time between waves emitted from a single source that produce stationary interference patterns. Coherence is the basis of applications in measurement and holography.

Thermal mechanisms of material processing take advantage of the high brightness (high power density) of a laser beam. *Athermal* (photonic) mechanisms are based on the short wavelength (high energy) of the beam, and the short duration of the pulses that can be produced. The beam characteristics influence the beam propagation and focusability, and therefore have an important effect on the suitability of the beam for material processing.

The characteristics of the emitted beam are determined by the cavity optics, the optical properties of the mirror coatings, and apertures and devices placed within the resonator. The beam can also be manipulated using optical devices placed outside the resonator. A propagating light wave must satisfy the complex wave equation

$$\nabla^2 U - \frac{1}{c^2}\frac{\partial^2 u}{\partial t^2} = 0 \qquad (3.5)$$

where U is the complex amplitude of the wave, and takes the form

$$U(r, t) = a(r)\exp[i\varphi(r)]\exp[i2\pi\nu t], \qquad (3.6)$$

The intensity, $I(r)$ is given by $I(r) = |U(r)|^2$.

Spatial Modes

Two spatial modes are commonly used to describe the beam: longitudinal and transverse. They are essentially independent of each other, since the transverse dimension in a resonator is normally considerably smaller than the longitudinal dimension.

Only light with a wavelength that satisfies the standing wave condition, $q\lambda = 2d$, will be amplified in the cavity, where q is a large integer referring to the number of nodes in the longitudinal standing wave, d is the cavity length (mirror separation), and λ is the wavelength. The longitudinal mode number is large in industrial lasers and is normally ignored when characterising the beam since it has little influence on the essential beam characteristics and performance. The transverse electromagnetic mode (TEM) is of the greater significance.

The TEM describes the variation in beam intensity with position in a plane perpendicular to the direction of beam propagation. It characterises the intensity variation in the beam resulting from its

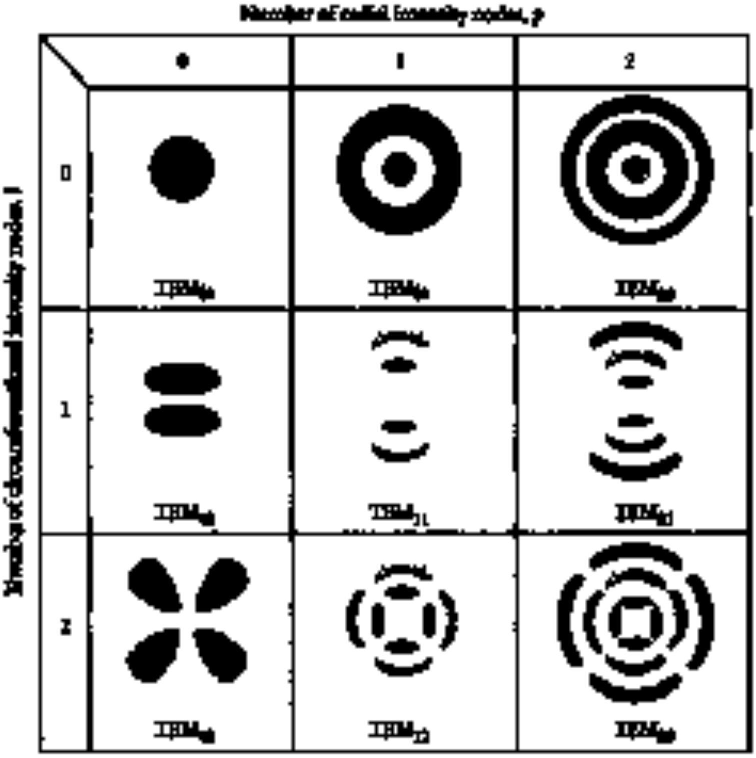

Figure 3.9 Transverse sections of transverse electromagnetic modes of circular symmetry

central axis. The TEM is determined by: the geometry of the cavity; the alignment and spacing of internal cavity optics; the gain distribution and propagation properties of the active medium; and the presence of apertures in the resonator. In gas lasers, gas flow and electrical discharge also influence the mode generated. The TEM is described by a set of subscripts that depend on the symmetry of the beam.

Cylindrical Symmetry

For a beam with cylindrical symmetry the subscripts of the TEM are *p*, *l* and *q*. *q* denotes the number of nodes (field zeros) in the standing wave pattern along the longitudinal (*z*) axis, and is not normally quoted. *p* and *l* indicate the number of nodes along the radius of the transverse beam section, and around the circumference of the central power ring, respectively, as illustrated in Fig. 3.9.

Mathematically, a cylindrical mode is defined by a Gaussian distribution multiplied by Laguerre polynomials, to describe the Laguerre–Gaussian mode. The equation for the complex amplitude of the mode is:

$$U_{lm}^{LG}(r,\phi,z) = C_{lm}^{LG}(1/w)\exp\left[-ik\frac{r^2}{2R}\right]\exp\left[\frac{-r^2}{w^2}\right]\exp[-i(l+m+1)\psi]$$
$$\times \exp[-i(l-m)\phi](-1)^{\min(l,m)}\left[\frac{r\sqrt{2}}{w}\right]^{|l-m|} L_{\min(l,m)}^{|l-m|}\left(\frac{2r^2}{w^2}\right)$$

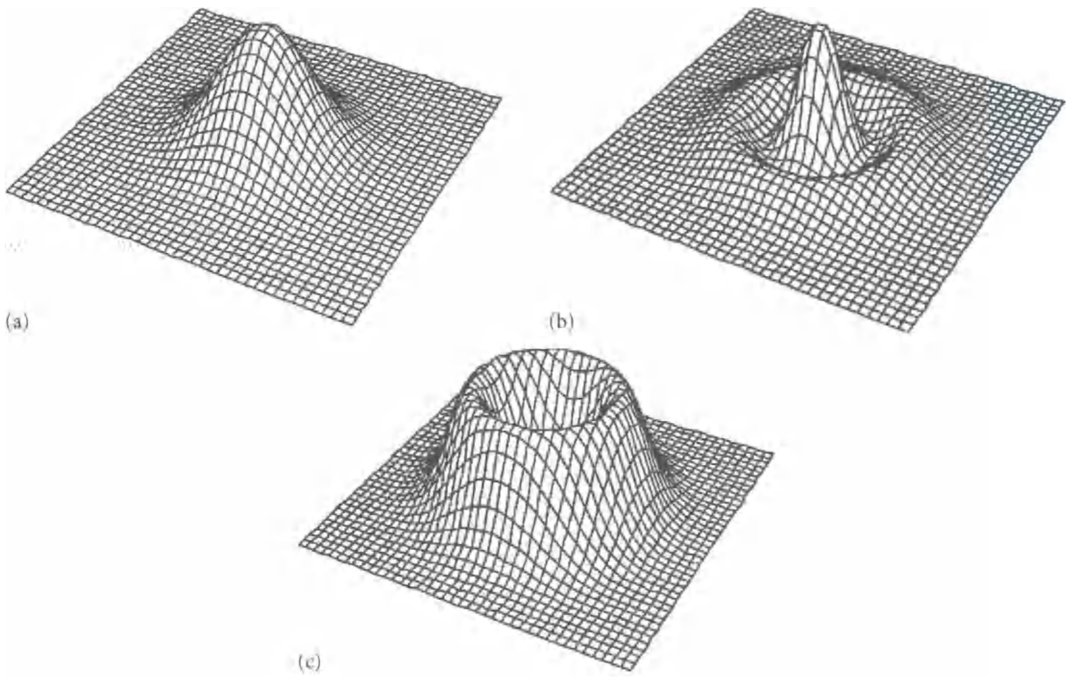

Figure 3.10 Intensity distributions in cylindrical (a) TEM$_{00}$, (b) TEM$_{10}$ and (c) annular (TEM$_{01^*}$) beam modes.

$$L_n(x) = \frac{e^x}{n!}\frac{d^n}{dx^n}\left(x^n e^{-x}\right)$$

$$C_{lm}^{LG} = \left(\frac{2}{\pi l!m!}\right)^{1/2} \min(l,m)! \tag{3.7}$$

The lowest order mode, TEM$_{00}$, refers to a beam with a Gaussian intensity distribution about a central peak, illustrated in Fig. 3.10a. The diameter of a TEM$_{00}$ beam of cylindrical symmetry can be defined by the points at which the intensity, I, has fallen to a given fraction of the peak intensity, I_0. The fractions $1/e$ or $1/e^2$ are often quoted for safety standards and manufacturing specifications, respectively, at which points the intensities have fallen to 36.8% and 13.5% of the peak, respectively.

The first order mode, TEM$_{10}$, refers to a central intensity distribution surrounded by an intensity annulus, Fig. 3.10b. Definitions of higher order beam diameters have been proposed, although there is currently no accepted standard. This is a major obstacle to comparing focused spot sizes between different beam modes. (The beam waist is not a good description of beam diameter since it is dependent only on the laser cavity and is independent of the beam mode.)

A beam with an annular intensity distribution can be produced from an unstable optical cavity because of the nature of the scraper mirror used to extract the beam. This is often referred to as TEM$_{01^*}$, illustrated in Fig. 3.10c. TEM$_{01^*}$ is strictly not a true mode since the intensity distribution changes between the near and far fields. An asterisk denotes the superimposition of two degenerate modes, TEM$_{01}$ and TEM$_{10}$, one rotated 90° about the axis relative to the other, which combine to form a composite intensity distribution of circular symmetry. An annular beam is characterized by a magnification, M, defined by the ratio of the outer diameter to the inner diameter. The magnification determines the focusability of the beam from an unstable resonator, in much the same way that the

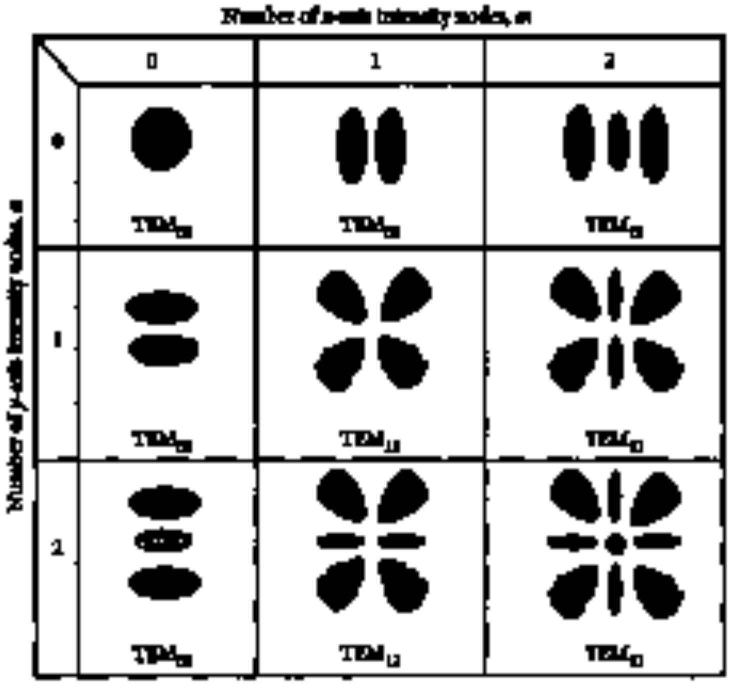

Figure 3.11 Transverse sections of beam modes of rectangular symmetry

Indices defining the transverse electromagnetic mode characterize beam focusability from a stable resonator. Focusability increases with magnification, whereas maximum power is typically obtained with relatively low values of *M* lying between 1.6 and 1.7. Unstable cavity designs are therefore a compromise between beam power and beam focusability.

Rectangular Symmetry

Cavities containing mirrors of circular cross-section normally produce cylindrically symmetrical transverse modes. However, square mirrors, the presence of Brewster-angle windows, or minor misalignments often cause optical cavities to oscillate with rectangular symmetry. End-pumped solid state lasers can produce rectangular modes because resonance can be sustained along off-axis ray paths within the cavity. In the case of rectangular symmetry, the subscripts *m*, *n* and *q* denote the number of nodes in the *x*, *y* and *z* directions, respectively, of a transverse section of the spatial intensity profile. The *x* direction is defined as the wider dimension, and the measurement is taken across the entire width/length of the pattern. Figure 3.11 shows a number of transverse beam modes of rectangular symmetry.

Mathematically, the rectangular mode is constructed by multiplying a Gaussian distribution by Hermitian polynomials, to define the Hermite–Gaussian mode. The equation for the complex amplitude of the mode is

$$U^{HG}_{mn}(x,y,z) = C^{HG}_{mn}(1/w)\exp\left[-ik\frac{x^2+y^2}{2R}\right]$$
$$\times\exp\left[-\frac{x^2+y^2}{w^2}\right]\exp[-i(m+n+1)\psi]H_m\left(\frac{x\sqrt{2}}{w}\right)H_n\left(\frac{y\sqrt{2}}{w}\right)$$

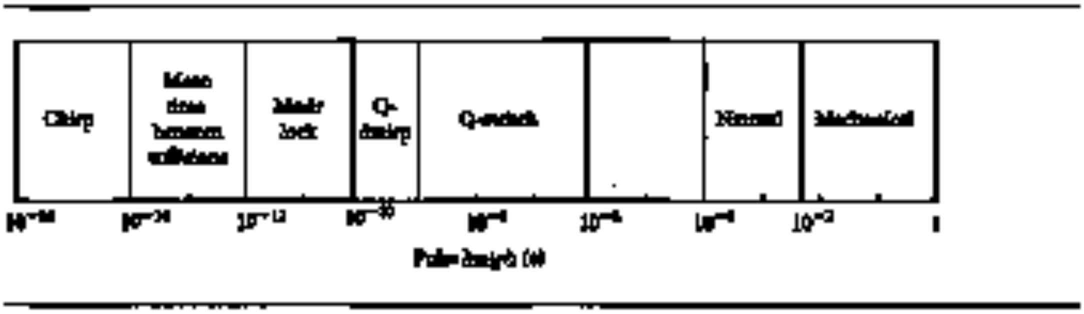

Figure 3.13 Time scales of pulsed laser output

$$H_m(u) = (-1)^m e^{u^2} \frac{d^m}{du^m}\left(e^{-u^2}\right)$$

$$C_{mn}^{HG} = \left(\frac{2}{\pi n! m!}\right)^{1/2} 2^{-N/2}. \tag{3.8}$$

Again, the lowest order mode, TEM_{00}, refers to a beam with a Gaussian intensity distribution about a central peak. Higher order modes contain intensity peaks along the *x* axis, the *y* axis, or both.

Fresnel Number

The size of the aperture in relation to the cavity length determines the dominant mode produced by the laser. A narrow cavity favours low order mode operation, because higher order modes are attenuated by the inner walls of the cavity. The Fresnel number, N_F, is a measure of the tendency for a stable laser cavity to operate low order modes.

$$N_F = \frac{a^2}{\lambda d} \tag{3.9}$$

where *a* is the radius of the smallest aperture in the system, λ is the wavelength, and *d* is the length of the cavity. An optical cavity with a low Fresnel number favours low order mode operation.

Temporal Mode

The temporal mode of the light emitted from a laser is determined by the number of energy levels in the active medium, their lifetimes, and the source of excitation. Three-level lasers such as ruby and dyes naturally produce pulses of light. Carbon dioxide and Nd:YAG lasers (four-level systems) are able to produce continuous wave output, but the temporal output mode may be changed through the use of various devices that can be inserted into the resonator, illustrated in Fig. 3.13 giving pulsed output down to the femtosecond (10^{-15} s) scale.

The simplest form of pulsed output is obtained by gating, or chopping the beam, which may be achieved through modulation of the excitation power (normal pulse), or by mechanical obstruction of a CW beam. The pulse is characterized by its peak power, shape, length and repetition rate. From these quantities, the pulse period (the reciprocal of the repetition rate), the pulse energy (the area under the power–time plot), and the *duty cycle* (the ratio of the pulse width to the pulse period), can be obtained. Enhanced pulses, or *super pulses*, denote the superimposition of a high power spike pulse on the leading edge of a gated or normal pulse, or on a CW beam.

Q-switching

The Q-factor, or quality factor, of a laser cavity is the ratio of the energy stored to the energy lost per cycle. A high value of Q indicates that energy is easily stored within the cavity, whereas a low value means that the contained energy will emerge rapidly. Q-switching is a technique by which short pulses of high peak power can be created in a laser with a continuous excitation source. The optical cavity contains a shutter, which when closed prevents laser action. However, during this time excitation energy continues to be absorbed, and more species are raised to the upper laser energy level, which increases the population inversion. When the shutter is opened a large number of excited species become available for stimulated emission, producing a large burst of energy until the upper level is depleted. The Q-switching mechanism must operate rapidly in comparison with the build-up of laser oscillations. The Q-switch is placed in the resonator between the more reflective back mirror and the active medium in order to maximize the blocking of laser action. Q-switching is commonly used with lasers in which the lifetime of the upper lasing level is long enough to store a significant amount of energy during blocking, notably high power solid state lasers. The technique is used in marking applications and some drilling operations. Four types of Q-switch are commonly used in lasers: mechanical; acousto-optic; electro-optic; and dye.

Mechanical Q-switches, such as rotating mirrors and mechanical choppers, were the first to be developed. Optical losses within the cavity are high except for the brief interval when the mirrors are parallel, or the chopper does not block the beam path. Feedback can also be provided by total internal reflection from the inner surface of a prism. These were popular in the early days of lasers. However, because of the rapid mechanical action, their mechanical reliability is poor, they are limited in the length of pulse that can be produced, and they are difficult to synchronize with outside events. The pulse length produced is relatively long, on the order of milliseconds.

An acousto-optical switch is an alternative that is based on the change in the refractive index of a medium caused by the mechanical strains that are induced by an acoustic wave as it travels through the medium. In effect the acoustic wave sets up a diffractive grating that can be used to deflect a beam of light. The medium is a transparent block of material, such as fused quartz, to which is attached a piezoelectric transducer. It is used for pulses on the order of microseconds.

Electro-optical Q-switches are based on the behaviour of polarized light as it passes through certain electro-optic materials when they are subjected to electric fields. Light passes through the material unchanged when no voltage is applied. However, when a voltage is applied, the polarization of the light is rotated 90°. A second element is a polarizer, which passes light that is in its original form, but not in its rotated form. When the voltage is applied, energy is stored in the population inversion. When the voltage is switched off, the stored energy is emitted as a pulse. Practical examples are the Pockels cell, which is a crystalline wave plate made from a material such as potassium dihydrogen phosphate, and the Kerr cell, which uses a liquid medium, such as nitrobenzene, to provide the phase retardation. Electro-optical Q-switches are more expensive than acousto-optical devices, but they can be used to produce very short pulses, on the order of nanoseconds.

Passive Q-switching is based on the action of saturable-absorbers. These are materials (often dye solutions) whose absorption depends on the incident light intensity. At high intensities the dye bleaches and allows light to pass through, thus allowing the formation of a giant pulse after a significant amount of energy has been stored. They are simple and inexpensive, but suffer from pulse jitter, dye degradation and synchronization difficulties.

Cavity Dumping

A cavity-dumped laser contains a switch and two fully reflecting mirrors. When the switch is open, laser action is permitted, and energy is built up within the cavity. A voltage is then applied to the switch, causing the polarization of the light passing through it to be rotated. Light is then emitted as a cavity-dumped pulse. The output coupler is thus the switch and not one of the mirrors. The pulse length is proportional to the round-trip time for photons, i.e. the length of the cavity. Pulses of nanosecond duration can typically be produced.

Cavity dumping is used to produce high energy pulses in lasers in which the lifetime of the upper lasing level is too short to enable Q-switching to be used, e.g. in argon and krypton ion lasers. It can also be used to produce very short or very high frequency pulses from lasers in which the desired pulse characteristics cannot be obtained through Q-switching alone.

Mode Locking

The number of axial modes in the output of a laser beam increases with the strength of excitation. By exciting the medium to just above a threshold level, light of a single wavelength is produced. However, if the excitation energy is increased significantly above the threshold level, emission at several wavelengths can thus be produced. Mode locking refers to the use of a modulating optical element to lock particular oscillation modes into phase, thus producing a train of pulses. The optical element is modulated at a frequency that matches the time taken for photons to travel the length of the optical cavity and back. The modulator is opened once per round trip, letting the pulse through. The resonance of these locked modes results in very short pulses of high intensity. Individual pulses can have different pulse lengths.

Mode locking is achieved using a fast optical gate. Electro-optic, acousto-optic and dye switches can be used. In the case of the last type, the dye absorbs the radiation in the cavity, except when all the modes are in step, both in phase and in spatial location. When this occurs, more energy is supplied to the dye than it can absorb and dissipate in the time of passage of the pulse through the dye. All the dye molecules are simultaneously in an excited state, making it saturated and allowing a part of the pulse to pass through. The length of the cell containing the dye is chosen to achieve the necessary conditions for saturation. Once such a mode-locked pulse occurs, part of it is fed back into the laser and with sufficient gain it saturates the dye each time it passes through. Thus, once started, the pulse remains in the laser as long as pumping continues.

The duration of the mode-locked pulses depends on several factors, including the bandwidth of light generated and the effectiveness of the modulator. Nd:YAG lasers, with relatively narrow bandwidths, produce mode-locked pulses of duration 50–60 ps, whereas high bandwidth dye lasers can produce pulses of duration 0.1 ps. In comparison with Q-switching and cavity dumping, mode locking produces the shortest pulse durations. Mode locking can be combined with other pulsing techniques, as used on the same.

Chirping

Chirping is the rapid changing – in contrast to long-term drifting – of the frequency of an electromagnetic wave, most often observed in pulsed operation of a source. It is a pulse compression technique that uses frequency modulation during the pulse. It is used in femtosecond-scale pulsed lasers, such as the Ti:sapphire source.

Frequency Multiplication

The fundamental wavelength of light produced by a laser, λ, is related to the energy of the photons, E, through the formula $E = hc/\lambda$, where h is Planck's constant (6.626×10^{-34} J s^{-1}) and c is the velocity of light (2.998×10^{8} m s^{-1}). The wavelength can be converted into a frequency, ν, by using the formula $\nu = c/\lambda$.

Some crystalline materials and liquids interact with light in a manner that results in the generation of a new frequency that is a multiple of the fundamental. Thus light of one wavelength can be transformed into light of another frequency. Frequency multiplication occurs in materials that exhibit a non-linear response to an electric field. An analogy is an atom in a crystal that is bound in a potential well that acts like a spring. In a linear crystal, as light interacts with the electrons, they are displaced by an amount proportional to the energy of the light. In a non-linear crystal this proportionality does not exist; when the electrons are displaced, the restoring force is no longer proportional to the driving energy. Oscillations then occur at frequencies other than that of the incident light, producing harmonics. An electromagnetic component can be produced that oscillates at twice the rate of the original wave, often with a polarization orthogonal to the fundamental. In order to obtain output of useful power – up to 50% of the incident intensity – a direction in the crystal is found at which the velocity of the fundamental beam matches that of the harmonic, i.e. the phases are matched. Thus green light of wavelength 532 nm can be produced from 1064 nm infrared light produced by an Nd:YAG laser.

Light with third and higher order harmonics can also be generated, normally in multiple-step processes. The efficiency decreases with increasing order. The main benefit of harmonic generation for material processing is the improved absorptivity of most metals at shorter wavelengths.

Raman Effect

When a beam of monochromatic light passes through a transparent substance the beam is scattered. The scattered light is not monochromatic, but has a range of wavelength that is shifted relative to that of the incident light. In terms of quantum theory, as a stream of photons collide with a particular molecule the photons will be deflected without change in energy if collisions are perfectly elastic. However, if energy is exchanged between the photon and the molecule, the collision is inelastic. The molecule can gain or lose discrete amounts of energy in accordance with quantum laws; the energy change must coincide with a transition between two molecular energy levels. The effect, known as Raman shifting, is used to change the frequency of laser light, enabling the output to be tuned.

Propagation

The propagation axis denotes the centreline of the beam of radiation. It is determined by the orientation of the resonator optics. The propagation of a Gaussian beam may be expressed in terms of the increase in beam radius, r_B, with distance from the laser, or the distance beyond the focal point of a focusing optic. The hyperbolic envelope created is known as the beam caustic. The *radius* of a beam can be written as a function of the *radius* of the focused beam, r_f, and the *distance* from the focal point, z:

$$r_B = r_f\left[1+\left(\frac{\lambda z}{\pi r_f^2}\right)^2\right]^{1/2} \tag{3.10}$$

where λ is the wavelength of the beam.

The beam radius can only be defined uniquely for a fundamental Gaussian beam. However, a modification to account for higher beam modes of order TEM$_{pl}$ can be written

$$r_B = r_f(2p+l+1)^{1/2}\left[1+\left(\frac{\lambda z}{\pi r_f^2}\right)^2\right]^{1/2} \tag{3.11}$$

where r_B defines the radius of a circle containing a defined amount of the beam. It can be considered comparable with the $1/e$ definition of a TEM$_{00}$ beam.

Waist

The beam waist refers to the minimum diameter of the beam. The location of the waist, z_w, in relation to the output coupler, is given by:

$$z_w = \frac{d g_2(1 - g_1)}{g_1 + g_2 - 2g_1g_2} \tag{3.12}$$

where g_1 and g_2 are defined by the characteristics of the optical cavity, as shown in Fig. 3.8, and d is the length of the optical cavity.

The waist normally lies inside the optical cavity. If the optical cavity contains a flat mirror the waist is located at the mirror.

Focused Spot Size

The diameter of a focused beam is directly proportional to its wavelength and inversely proportional to the numerical aperture of the objective lens. The numerical aperture is a value that depends on the diameter of the focusing optic, its radius of curvature and the material from which it is made. If we wish to minimize the focused spot diameter, we select a beam of short wavelength and an objective lens with a large numerical aperture. More details of the properties of a focused beam can be found in Chapter 4.

Rayleigh Length

The Rayleigh length or range, z_R, is the distance along the path of propagation from the beam waist to the plane in which the beam diameter exceeds the beam waist diameter by a factor of $\sqrt{2}$. It characterizes the near field or collimated region of the beam, and is defined for a TEM_{00} mode beam as

$$z_R = \frac{4\pi r_f^2}{\lambda} \tag{3.13}$$

where λ is the wavelength and r_f is the radius of the focused beam. Beyond the Rayleigh length the beam will expand at a constant rate or angle – the far field beam divergence. A Gaussian beam has the longest Rayleigh range, and the smallest far field divergence.

The Rayleigh range for higher order mode beams can be expressed in terms of the beam's quality factor, K (which is defined below):

$$z_R = \frac{4\lambda}{\pi}\frac{f^2}{K} \tag{3.14}$$

where f is the focal number of the optic, given by $f = F/d_b$. (F is the focal length and d_b the diameter of the optic.) It is a useful scale unit for measuring propagation distance beyond an optic.

Radius of Curvature

One of the characteristics of laser light is its coherence. If a surface is constructed containing all the points of common phase in a Gaussian beam, that surface would be a sphere with a particular radius of curvature, R. As the beam propagates, the radius of curvature changes: it is infinite at the beam waist, decreasing sharply after the waist to a minimum at the Rayleigh length, after which it increases again.

At larger distances it is equal to the distance from the waist. The variation of R with distance from the waist, z, is given by:

$$R = z\left[1 + \left(\frac{\pi r_f^2}{\lambda z}\right)^2\right] \tag{3.15}$$

where λ is the wavelength and r_f is the beam radius at the waist.

If the mirror curvature exactly matches the radius of curvature of a Gaussian beam, the energy in the wave, which travels perpendicular to the wavefront, will be reflected back on itself, and the resonator will be stable.

Fields

The terms *far field* and *near field* are frequently used when describing laser beams. The intensity distribution across the transverse beam cross-section at the exit of the laser is known as the near field mode. The beam propagates from the laser according to the laws of optics, but diffraction effects tend to modify the intensity distribution. Eventually a point is reached at which the beam has spread to such a degree that its area is considerably larger than that predicted by optical calculations, and diffraction effects totally dominate the intensity distribution. This is the far field distribution, and generally occurs at a distance of around the Rayleigh length from the beam waist.

Divergence

Divergence is a measure of the tendency for the beam to spread as it propagates from the laser. Since the beam emitted from many commercial gas lasers is symmetrical, divergence is normally measured in plane angles (radians), rather than solid angles (steradians). The divergence, θ, of a Gaussian beam of wavelength λ, after it has passed through the beam waist of diameter d_0, is given by:

$$\theta = \frac{2}{\pi}\frac{\lambda}{d_0}. \tag{3.16}$$

The larger the beam waist diameter, the smaller the divergence.

If the distance between the laser and the workpiece is large, the beam divergence should be small, preferably less than 1.0 mrad (half angle). Short wavelength lasers are therefore better for small divergence applications. A TEM_{00} beam mode has the lowest beam divergence. Low divergence results in a smaller focused spot and a greater depth of focus.

Any system that moves optics along the beam path must take divergence into account, since the size of the beam at the focusing optic varies. Divergence is typically 1 mrad for a TEM_{00} beam and 20 mrad for a multimode beam. A value of 2–3 mrad is common for industrial CO_2 lasers. Beam divergence has implications for the size of the optics that must be used; the beam can grow significantly over several metres in a large workstation. For example, the 25 mm diameter TEM_{00} beam emitting from a CO_2 laser can grow to around 100 mm over a path length of 40 m.

Quality

The minimum size to which a laser beam can be focused is the diffraction limit, which refers to the minimum diameter of a (Gaussian) TEM_{00} beam, given by λ/π, where λ is the beam wavelength. The quality of a beam is a measure of its focusability (spot size and focal length), and can be measured in various ways.

The K factor expresses beam focusability in terms of that of a TEM$_{00}$ beam:

$$K = \frac{\lambda}{\pi}\frac{4}{d_0\theta} \tag{3.17}$$

where d_0 is the diameter of the incident beam and θ is the full beam divergence angle. $K = 1$ for a TEM$_{00}$ beam, and is less than 1 for higher beam modes. Industrial gas laser beams typically have K values in the range 0.7–0.2. The closer the K factor is to 1 the better the quality of the laser beam. This notation is particularly popular in Germany.

An analogous beam quality system uses the M^2 notation, where

$$M^2 = \frac{\pi}{\lambda}\frac{d_0\theta}{4}. \tag{3.18}$$

$M^2 = 1/K$ for a TEM$_{00}$ beam ($K = 1$). A beam with an M^2 value of 1.3 can be thought of as being 1.3 times diffraction limited, and would produce a focused waist diameter 30% larger than the TEM$_{00}$ mode. M can be calculated approximately for higher modes of circular symmetry, TEM$_{pl}$, using the formula

$$M = \sqrt{2p + l + 1}. \tag{3.19}$$

For a pure TEM$_{20}$ beam, $M^2 = 5$. The lower the M^2 value, the higher the beam quality. This notation is particularly popular in the United States. (M^2 is used rather than M because it represents the ratio of the divergence angle to that of a TEM$_{00}$ beam.) The M^2 factor is sometimes referred to as the Q-factor (distinct from the cavity quality factor). (The M^2 factor should not be confused with the magnification of an unstable beam, for which the symbol M is normally used.)

The beam parameter product, BPP, is normally quoted when discussing the quality of a laser beam produced from a solid active medium, or delivered from a fibre optic. The beam parameter product is proportional to the beam diameter (the fibre diameter of a fibre optic) and the beam divergence angle, and is defined as

$$BPP = \frac{d_0\theta}{4} = M^2\frac{\lambda}{\pi}. \tag{3.20}$$

BPP is measured in units of mm · mrad.

The benefits of a high beam quality for material processing are three-fold. A small focal diameter gives high process efficiency, low energy input, and narrow cut kerfs and welded seams. A slim processing head can be constructed, which provides high processing flexibility. A large working distance enables remote processing to be carried out in several locations sequentially, and a large depth of focus improves tolerance to the position of the focal plane during processing.

Bandwidth

The emission line used for laser operation has a finite spectral width. A certain amount of line broadening, or bandwidth, is associated with any form of electromagnetic radiation. The distribution of frequencies about the line defines the emission line shape. The bandwidth defines the degree of monochromaticity of the beam. It can be measured in terms of wavelength, frequency, wave numbers or coherence length. The wave number refers to the number of wavelengths that fit into 1 cm. The coherence length is the distance over which the laser remains sufficiently coherent to produce interference fringes. It is inversely proportional to the bandwidth expressed in frequency or wavelength, and is equal to the reciprocal of bandwidth in wave numbers. In terms of wavelength, there are a number of discrete lines either side of the central peak. The bandwidth measurement is made at an intensity of half that of the peak, and is defined as the full width half maximum (FWHM) measurement.

In a homogeneously broadened laser each individual atom has a bandwidth equal to the total laser bandwidth. If a particular photon can interact with one of the atoms, it can interact with all of them. Homogeneous broadening is mainly caused by collisions of gas molecules with each other, other species in the mixture, or the walls confining the gas. These cause perturbations in the energy of the photons emitted. As the pressure in the laser increases, the bandwidth of the laser increases because of the increased number of collisions in a given time. In solid state lasers, thermal line broadening is caused by interactions between the laser species and vibrations in the crystal lattice. Lattice vibrations are quantized, and referred to as phonons. Bandwidth is normally relatively easy to reduce in a homogeneously broadened laser because all the atoms can still contribute to stimulated emission in the narrower bandwidth.

Heterogeneous broadening refers to a condition by which different atoms contribute to the gain at different frequencies. This may be a result of inhomogeneities in the active medium, such as defects, which cause the environment to vary from point to point in a solid. The Doppler effect is a source of heterogeneous broadening, and is significant in most gas lasers. Since the individual atoms are moving in random directions, at random speeds, their total emission covers a range of frequencies, in the same way that sound from a moving object changes frequency depending on the relative motion with the observer. The hotter the gas, the broader the bandwidth. Emission lines are generally broadened heterogeneously. Those atoms that contribute to gain outside the reduced bandwidth cannot be stimulated to emit in the narrowed bandwidth, and therefore the total power is reduced.

The bandwidth may be made narrower by cooling the active medium to reduce thermal broadening in a solid state laser, or to reduce Doppler broadening in a gas laser. The feedback of the resonator may also be modified to control the laser bandwidth. This may be achieved by using mirrors with a narrow bandwidth of reflection. A prism inside the cavity may also be used to direct only light in the centre of its bandwidth towards the mirrors. One of the mirrors may be replaced with a grating, which reflects different wavelengths at different angles. When aligned correctly, only light with a wavelength at the centre of the population inversion is reflected.

Coherence

A light source emits a sequence of light waves, each of a certain length – the coherence length. This is the distance that the light will travel before its coherence changes. The coherence length, l_{coh}, depends on the wavelength, λ, and the bandwidth, $\Delta\lambda$:

$$l_{coh} = \frac{\lambda^2}{\Delta\lambda}. \tag{3.21}$$

Two waves can only interfere when light quanta from the same emission process interact. Therefore, natural light sources which have a very large bandwidth, and consequently a very short coherence length, do not exhibit interference phenomena.

A coherence time, t_{coh}, can then be defined:

$$t_{coh} = \frac{l_{coh}}{c} \tag{3.22}$$

where c is the velocity of light. Coherence time can be understood as the temporal difference between two light waves, originating from the same source, that produce stationary interference patterns. This aspect of coherence considers only point sources and interference between temporally shifted waves, and therefore is referred to as temporal coherence.

Brightness

Brightness, B, is a measure of the intensity of light at a particular location. It is defined as the emitted power, q, per unit area, A, per unit solid angle, Ω:

$$B = \frac{q}{A\Omega}. \tag{3.23}$$

Brightness depends on the intensity of the source and the extent to which the light diverges after leaving the source. Since the laser can produce very high levels of power in very narrowly collimated beams, it is a source of high brightness energy.

Intensity

The intensity, I, obtained by focusing a beam of light is directly proportional to the brightness, B:

$$I = B\frac{\pi w_0^2}{F^2} \tag{3.24}$$

where F is the optic focal length and w_0 is the beam waist diameter.

The beam intensity can be related to temperature through the Stefan–Boltzmann law:

$$I = \sigma T^4 \tag{3.25}$$

where σ is the Stefan–Boltzmann constant (5.67×10^{-8} J m^{-2} s^{-1} K^{-4}), and T is the absolute temperature of the radiating surface. Thus it can be seen that the intensity of the sun, approximately 10^4 W cm^{-2} corresponds to a surface temperature of approximately 6500 K, whereas an intensity of 10^6 W cm^{-2}, used in keyhole welding, produces a temperature of approximately 26 900 K – sufficient to vaporize any known metal.

Note that the intensity of a beam can be increased by focusing, but the brightness cannot.

Polarization

Light is composed of electric and magnetic waves oscillating in orthogonal planes. The polarization of light characterizes the relationship between the plane of oscillation of the electric field and the direction of propagation. Only the electric field is normally considered since it is the most important when considering interactions with materials. The polarization of a laser beam affects the amount of light absorbed in many material processing applications.

The plane of incidence is the plane that contains the incident beam and the normal to the surface. If the electric vector of the light lies in the plane of incidence, the light is said to be p-polarized. If it is normal to the plane of incidence, it is s-polarized (from the German word senkrecht, meaning vertical or perpendicular). If it is at any other angle, it may be resolved into components of s- and p-polarization. Light sources with s- and p-polarization interact differently with a material surface as the angle of incidence, φ, increases. When $\varphi = 0$, s and p cannot be differentiated, and so the reflectivity is the same for all polarizations. As φ increases, the reflectivity for s-polarized light increases smoothly, until it becomes unity at 90°, or grazing incidence. In contrast, the reflectivity of p-polarized light decreases monotonically until it becomes zero. The angle at which complete absorption occurs is called the Brewster angle. Beyond this angle, reflectivity increases sharply until it too reaches unity at grazing incidence. The Brewster angle, φ, is related to the index of refraction, n, by

$$\varphi = \tan^{-1}(n). \tag{3.26}$$

Many different states of polarization are possible; two are illustrated in Fig. 3.13.

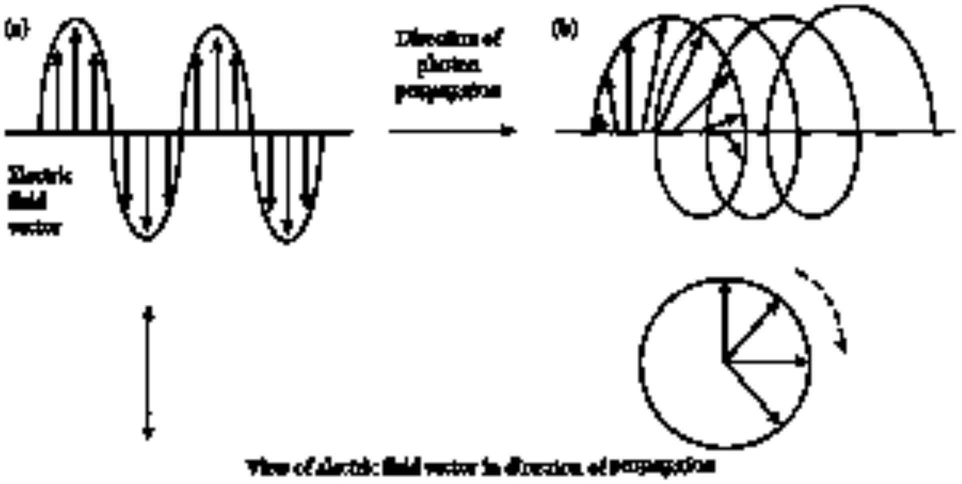

Figure 3.15 (a) Linear (plane) polarization and (b) circular polarization shown in terms of the direction of the electric field vector

In the state of linear, or plane, polarization, Fig. 3.15a, the electric field oscillates in one plane only. If the plane is vertical, the light is said to be vertically polarized. Similarly, in horizontally polarized light the electric vector oscillates in a horizontal plane. The *s* and *p* components of polarization are in phase. Plane polarization is often found in commercial lasers, and originates from the reflections within the optical cavity.

Circular polarization, Fig. 3.15b, describes light in which the electric field vector has a constant amplitude and rotates with a constant angular velocity around the axis of propagation. It may rotate clockwise or anticlockwise. The *s* and *p* components are 90° out of phase. Light of linear polarization may be converted to circular polarization through the use of a quarter wave plate (Chapter 4).

Elliptical polarization describes light in which the electric field vector rotates with a constant angular velocity around the axis of propagation, and the absolute value of the field vector also varies regularly. The locus of the projection of the electric field vector describes an ellipse.

If the electric field oscillates in random directions, the light is randomly polarized. Such radiation can be thought of as comprising two orthogonal linearly polarized waves of fixed direction whose amplitudes vary randomly over time and with respect to each other. Natural sunlight is randomly polarized.

Beam polarization affects the amount of energy absorbed by the material, and hence the efficiency and quality of laser processing. This is described for cutting in Chapter 14 and welding in Chapter 16. The polarization state of the beam must be established in order to optimize the processing parameters.

LASERS FOR MATERIAL PROCESSING

Lasers for material processing may be classified by: active medium (gas, liquid or solid); output power (mW, W or kW); wavelength (infrared, visible and ultraviolet); operating mode (CW, pulsed, or both); and application (micromachining, macroprocessing etc.) – to name a few. Since the state of the active medium determines the principal characteristics of the laser beam for material processing, it is used here as a primary means of classification: gases (atoms, molecules, ions and excimers); liquids (principally organic dyes); and solids (insulators and semiconductors). This categorization is shown in Fig. 3.16.

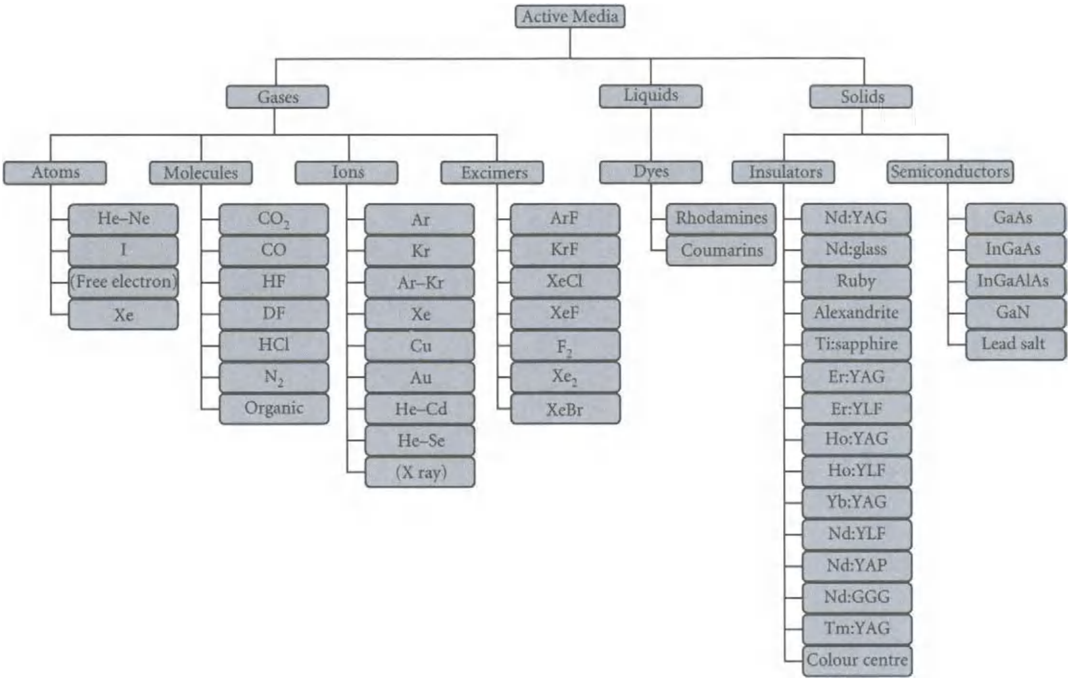

Figure 3.14 Lasers for material processing categorized by the type of active medium (lasers shown in parentheses are allocated to the most representative group.)

Within each sort of active medium, the lasers are presented here in a format that facilitates understanding of the mechanism of light generation (electronic transitions in atoms, vibrational transitions in molecules etc.). The fixed ordering represents their popularity for industrial material processing (ArF, KrF, XeCl ...). Figure 3.14 can be used as a guide to locate a particular laser in this chapter: the lasers are presented in the order shown. Further details of each laser can be found in Appendix B.

Figure 3.15 shows an alternative means of presenting a selection of material processing lasers, in a chart with axes of wavelength and average power. Operating regions of different lasers can then be distinguished, and power levels appropriate for material processing selected. Graphical presentation facilitates understanding of the relationships between variables, and is a central feature of the book. We return to the use of charts and diagrams in laser material processing in Chapter 6.

ATOMS

Light generated in gaseous active media of atoms is considered first since atomic transitions are well defined and relatively straightforward. Transitions take place between electronic energy levels separated by a gap large enough to produce photons of high energy, corresponding to wavelengths in the ultraviolet and visible regions of the electromagnetic spectrum.

Helium–Neon

The active medium in the helium–neon (He–Ne) laser is neon, which is typically present in quantities less than 15% – the balance being helium. The first step involves exciting helium in an electrical discharge. Helium atoms then transfer energy to neon atoms by resonance, promoting them to higher

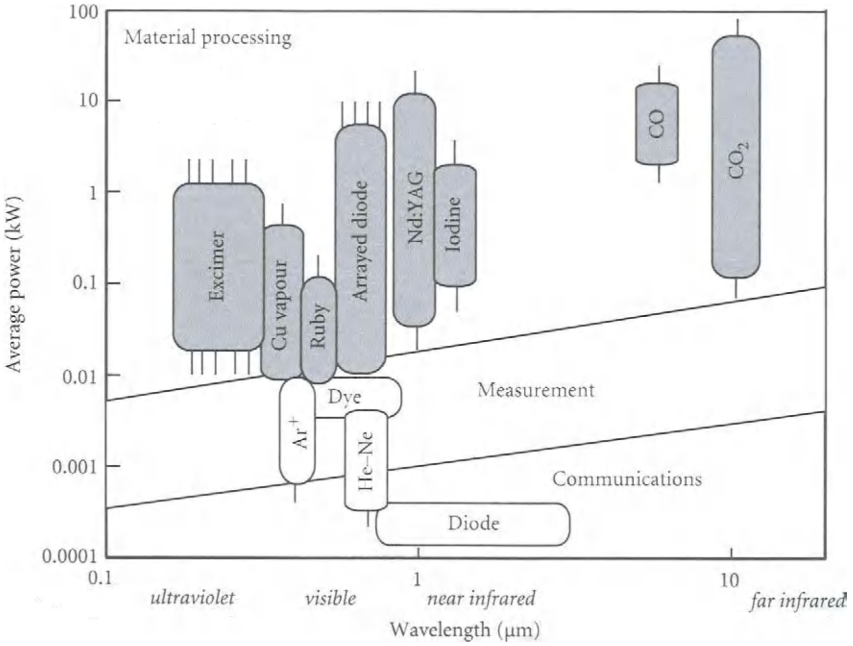

Figure 3.15 A selection of commercial lasers characterized by wavelength and average power, shown on a background of applications (lines indicate the principal output wavelengths, and those used principally for industrial material processing are shaded)

energy levels. The laser operates on a four-level principle (absorption, upper laser, lower laser, and ground states), illustrated in Fig. 3.4, and so continuous wave light can be produced with high efficiency.

The optical cavity is small in diameter. A large ratio of surface area to volume is desirable in order to maintain the population inversion by allowing Ne atoms to lose energy through collisions with surfaces, enabling them to participate in excitation again. Excitation is produced in a longitudinal DC electrical discharge. The gain is relatively low, and therefore the transmission of the output coupler is necessarily low, around 1–2%. Only very small losses can be tolerated in the cavity, and so high quality mirrors are needed.

Output close to infrared was obtained in the first He–Ne laser, but it was the discovery of visible red radiation of high beam quality that resulted in myriad applications, including barcode readers at supermarket checkouts, pointers, surveying equipment, scientific research, holography and light shows. Modern He–Ne lasers for illumination purposes produce output of a few milliwatts in a variety of colours: green (543 nm); yellow (594 nm); orange (612 nm) and infrared (1523 nm). Early material processing applications included laser printers and medical procedures. However, because of their low cost and compactness diode lasers have replaced them in many such applications. But the high beam quality is difficult to obtain with diode laser output – this is the key to using He–Ne lasers in modern methods of material processing on the microscopic scale.

Iodine

Atomic iodine is the active medium in the chemical oxygen iodine laser (COIL) – a member of the chemical laser family. Molecular oxygen is first excited by an exothermic chemical reaction between gaseous chlorine and an aqueous solution of hydrogen peroxide and potassium hydroxide. Molecular iodine (I_2) is added to form a gas mixture comprising about 1% I_2, which is converted to the atomic form (I) through dissociation by energy transfer from the excited oxygen. Energy is then transferred by resonance between metastable excited oxygen and atomic iodine, which is pumped to the excited state. Near infrared light of wavelength 1315 nm is generated through subsequent electronic transitions in iodine. The lower energy transition level is the ground state, where molecular iodine forms, allowing the population inversion to be maintained. The temperature must be maintained around 150°C to sustain laser action.

A high beam quality is produced because of the gaseous nature of the active medium. The output wavelength lies in the range corresponding to minimum power loss in silica; it is therefore suitable for fibreoptic beam delivery. Hydrogen peroxide and iodine are consumed, necessitating replenishment during operation. The resonator can be scaled relatively easily to achieve high power levels.

Multikilowatt iodine lasers have the potential to compete with CO_2 and Nd:YAG sources in comparable materials processing applications, such as cutting, welding, machining and surface treatment, provided that their operating costs can be reduced. The near infrared wavelength of the beam provides advantages over far infrared CO_2 laser radiation: a smaller focused spot can be produced, and energy is coupled more efficiently with metals. Fibreoptic transmission of very high power levels provides advantages over Nd:YAG laser light. As part of the US Air Force Airborne Laser project, units capable of generating pulsed megawatt power levels have been installed in a fleet of Boeing 747 aircraft; one is shown in Fig. 2.5. The beam is focused through a lens mounted in a turret in the nose to destroy missiles moments after launch – laser material processing in space.

Free Electron

A beam of electrons generated in an accelerator can be passed through an array of magnets, causing the electrons to be bent back and forth (wiggled). The electrons emit radiation, based on the conservation of momentum. The frequency of radiation can be changed by varying the electron energy, the magnetic field, or the spacing of the magnets. Heat is carried away in the electron beam itself.

Light in the wavelength range 500–8000 nm can be produced. The wavelength and spectral width of the light is dependent on the number and spacing of the magnets. If the electron beam is pulsed to emit a spatial series of bunches, with a separation corresponding to the emission wavelength, the output becomes coherent. The emission bandwidth is not dependent on the optical bandwidth of a material such as a gas, liquid or solid, and so light can be emitted over a much wider wavelength range than is possible with a conventional laser.

Free electron lasers operating in the visible to mid-infrared regions of the electromagnetic spectrum have been constructed. The variable temporal structure and broadband tunability of laser media is potentially suitable for a variety of surgical applications. When used to vaporize cells, less damage is caused to surrounding tissue than with conventional lasers.

Xenon

Atomic xenon (Xe) is mixed with argon or helium to form the active medium of the Xe laser. It emits radiation in the far infrared on a number of distinct lines. Beam quality is high because of the gaseous nature of the active medium. Pulses with energy on the order of tens of joules, of microsecond duration, can be produced. They are used for material processing by thermal mechanisms, and applications are being developed that are similar to those for chemical lasers (discussed below).

MOLECULES

Energy transitions in molecules are those between vibrational and rotational energy levels. Transitions between vibrational states of the same electronic level are possible, as in carbon dioxide. Also possible are transitions between vibrational states of different electronic levels, as in nitrogen.

Carbon Dioxide

Gaseous carbon dioxide (CO_2) is present in amounts between 1 and 5% as the active medium of commercial CO_2 lasers. The remaining volume comprises helium (60–85%), nitrogen (13–55%) and small amounts of other gases; the exact composition depends on the design of the optical cavity, the gas flow rate and the output coupler used. High gas purity is necessary, typically 99.995% for helium and nitrogen, and 99.990% for carbon dioxide.

Nitrogen increases the efficiency of excitation by facilitating the absorption of energy, which is subsequently transferred to the CO_2 molecule. Carbon dioxide may be excited directly in an electric discharge, but molecules are excited to states in addition to the upper laser level, and so the efficiency of the process is low. A more efficient means is by indirect excitation via excited N_2 molecules. Nitrogen is a diatomic molecule and has only one mode of vibration, which can be induced easily by collision with high energy electrons in the discharge. The vibrational levels of N_2 lie close to the upper laser level of CO_2, and the lifetime of N_2 in the excited state is long; the probability that energy is transferred from N_2 to CO_2 by resonance is therefore high. This two-step process is more rapid than direct excitation, and results in a four-fold increase in laser power.

Helium is added to expedite cooling, which is necessary if the gas mixture is to continue stimulated emission. Excited CO_2 molecules lose energy in the form of heat by colliding with helium atoms. Sufficient energy is lost such that the CO_2 molecules return to the ground state, becoming available for excitation again. The high thermal conductivity of He (around six times that of CO_2 and N_2) enables energy in the gases to be conveyed away from the discharge region. A more stable and uniform discharge is then produced, allowing a higher working pressure to be used, which also aids in the generation of a high power beam.

Pollutants are generated during operation. Hydrogen ions – generated from the decomposition of water vapour – destabilise the discharge and degrade the operating efficiency. Hydrocarbons decompose forming carbon deposits on mirrors, reducing the gain of the laser. Nitrogen oxides, formed from reactions between dissociated nitrogen and oxygen (itself produced by the dissociation of CO_2 into CO and O_2), are harmful for the operation of the laser. Water vapour is added in small quantities to reduce CO_2 dissociation. This increases the lifetime of the gas. The addition of xenon in small amounts increases output power and efficiency, mainly because of its effect on the electron energy distribution, which is favourable for the vibrational excitation of CO_2 and nitrogen.

The CO_2 laser operates on a four-level basis, illustrated in Fig. 3.4. Photons are generated by transitions between modes of vibration in the linear triatomic CO_2 molecule. The molecule has three distinct vibrational modes: bending, symmetric stretching, and asymmetric stretching, illustrated in Fig. 3.14, which are associated with frequencies of 2.0, 4.2 and 7.0 × 10^{13} Hz, respectively. In the asymmetric stretching mode the two oxygen atoms move in the same direction, while the carbon atom moves in the opposite direction. In the symmetric stretching mode the two oxygen atoms move in opposite directions while the carbon atom is stationary. The bending mode comprises two degenerate vibrations. In all cases, the centre of mass of the molecule does not move. The vibrational state is denoted by three quantum numbers (v_1, v_2 and v_3) that represent the number of vibrational quanta (the level

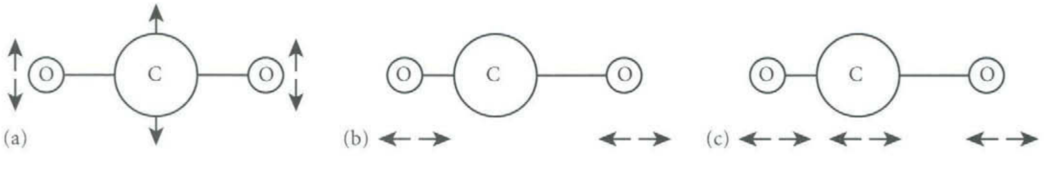

Figure 3.14 Modes of vibration of the carbon dioxide molecule: (a) bending; (b) symmetric stretching; (c) asymmetric stretching

of excitation) in the symmetric stretching, bending and asymmetric stretching modes, respectively. (A superscript to the bending mode number represents additional quanta for the rotational mode.)

The initial stage of light generation involves vibrational excitation of CO_2 molecules from the ground state (00^00) into the asymmetric stretching mode (00^01) by both inelastic collisions with low energy electrons, and resonant energy transfer from vibrationally excited N_2 molecules. The laser transition involves a change in the mode of vibration from the (00^01) state to the symmetric stretching state (10^00). This results in a loss of energy, emitted in the form of an infrared photon with a wavelength near 10.6 μm. (Energy may also be lost through a transition to the bending mode (02^00) with the emission of a photon of wavelength near 9.6 μm, but the probability of this transition is only around 5% of that of the 10.6 μm transition. In addition, the resonator is designed to favour 10.6 μm radiation.) The quantum efficiency of the 10.6 μm transition is relatively high (around 40%) hence the interest in this system for high power output.

For the process to continue, the CO_2 molecule must return to its ground state so that it can be excited again. This can occur by a number of mechanisms. Energy can be transferred by resonance to other CO_2 molecules, such as those in the (02^00), (01^10) or (00^01) states; energy is thus redistributed without a total loss. In contrast, non-resonant collisions with the walls of the resonator, other CO_2 molecules, or foreign atoms result in the conversion of the energy of (01^10) molecules into heat, resulting in a loss in total energy. Helium is a particularly effective agent in this respect, which explains its high volume in the gas mixture.

Electrical methods are the most common means of exciting industrial CO_2 lasers. Both direct current (DC) and alternating current (AC) techniques are used. AC excitation may be high frequency (HF, 20–50 kHz), medium frequency, or radio frequency (RF, 2–100 MHz). In the last category, excitation frequencies of 13.56 and 27.12 MHz are popular in commercial designs.

Commercial CO_2 lasers are available in five basic configurations, which characterise the geometry of gas flow in the optical cavity: sealed; transversely excited atmospheric pressure; slow axial flow; fast axial flow; and transverse flow. Typical characteristics of these designs are given in Table 3.1.

Sealed

The optical cavity of a sealed CO_2 laser is made from a large bore glass tube or a square metal or dielectric tube about 2 mm in width. The latter is often referred to as a waveguide laser, since the

Table 3.1 Characteristics of commercial CO_2 laser designs

	Sealed	TEA	Slow axial flow	Fast axial flow	Transverse flow
Optical cavity design	Stable	Stable/unstable	Stable	Stable/unstable	Unstable
Gas, He–N_2–CO_2–H_2/O_2–CO (vol. %)	73–24–8–0–4	73–16–8–0–4	72–19–9–0–0	67–30–3–0–0	60–25–10–5–0
Gas flow rate (m s^{-1})	–	–	5–10	500	20
Gas pressure (mbar)	5–14	1000	6–14	70	30
TEM	TEM_{00}, multimode	TEM_{00}, multimode	TEM_{00}, multimode	TEM_{00}, multimode	Multimode
Gain (W cm^{-3})	20–50	0.5	0.5	5–10	4–6
Gain (W m^{-1})	90	100	100	1000	6000
Wall plug efficiency (%)	5–15	5–20	5–15	5–15	5–10
Cooling	Conduction	Conduction	Conduction	Convection	Convection
Ergonomics	Portable	Portable	Fixed	Fixed	Fixed

internal cavity surfaces are highly reflective and are an active element of the cavity. A totally reflecting focusing mirror and a partially transmitting output coupler bound the cavity, which is sealable and is permanently aligned.

RF excitation, applied transverse to the resonator axis, is preferred: the source is small, a larger volume can be excited producing more power, and contamination caused by electrode sputtering is avoided, which means that continuous gas replenishment is not needed. However, the discharge causes CO_2 to dissociate into CO and O_2, which reduces output power and corrodes internal parts. Hydrogen or water may be added to regenerate CO_2. A heated nickel cathode may be used to catalyse the recombination reaction. The gas mixture is cooled during low duty cycle applications by conduction through the cavity walls and natural convection via external fins. Forced air or liquid cooling is used in more demanding applications.

The narrow design of the optical cavity produces a high quality beam mode. The gain per metre length of discharge is relatively low because of the narrow cavity, but the gain per unit volume is high because the entire cavity section can be used to generate light. The beam is normally extracted as a square wave pulse of high frequency, high peak energy and low average power. Because of their construction, sealed lasers have a particularly stable output and mode. The power available from a sealed cavity is limited by two factors: the restricted volume of gas which can be excited in units of a practical size, and the rate at which heat can be removed by conduction.

Since the resonator contains no moving parts, and gas flow is not necessary, no external gas connections are required. The head can therefore be transported easily, and mounted on a robot to provide a high degree of processing flexibility. All of the power generated in the laser may then be used for processing since complex optical trains are not required for beam delivery. The laser can operate for many thousands of hours before the gas mixture needs to be changed. Sealed CO_2 lasers are relatively cheap, and are capable of marking, fusing, scribing and engraving the surface of a wide range of materials, as well as through-thickness cutting, trimming, welding and perforating thin sheet materials. Such lasers are used widely in desktop manufacturing systems, and are being used increasingly in surgical procedures.

A pseudo-sealed CO_2 laser design is also available, capable of producing multikilowatt output power. The unstable optical cavity is RF excited via two parallel copper electrodes of large surface area, which produce a relatively high power density. The electrodes are water cooled and their spacing is close: they are therefore able to dissipate heat generated in the gas (referred to as diffusion cooling). A conventional gas circulation system is therefore not required for cooling. The gas consumption is only around 2 L hr^{-1} in comparison with about 85 L hr^{-1} for fast axial flow designs of the same output, which means that only a small cylinder mounted near the head is required, reducing maintenance requirements. (Such lasers can be used for 12 months continuously.) The unit generates a high quality beam mode ($M^2 < 1.45$) and occupies 15% of the volume of a fast axial flow laser of equal power. A schematic illustration of a CO_2 slab design is shown in Fig. 3.17a, and a production laser is shown in Fig. 3.17b.

Transversely Excited Atmospheric Pressure

The gas mixture used in a transversely excited atmospheric pressure (TEA) carbon dioxide laser is given in Table 3.1. Carbon monoxide and hydrogen may be added to counteract the dissociation of carbon dioxide, and to produce a more uniform discharge and increase output power. A gas mixture that reduces the pulse decay time is used when high pulse rates are required. Gas pressures up to several atmospheres enable high power levels to be generated per unit volume of laser gas.

The gas mixture is excited by an electrical discharge applied transverse to the optical axis. Since the gas pressure is relatively high, large voltages are required for excitation. The electrodes, which are profiled to give a more uniform field, may be placed longitudinally along the optical axis to reduce the potential difference required.

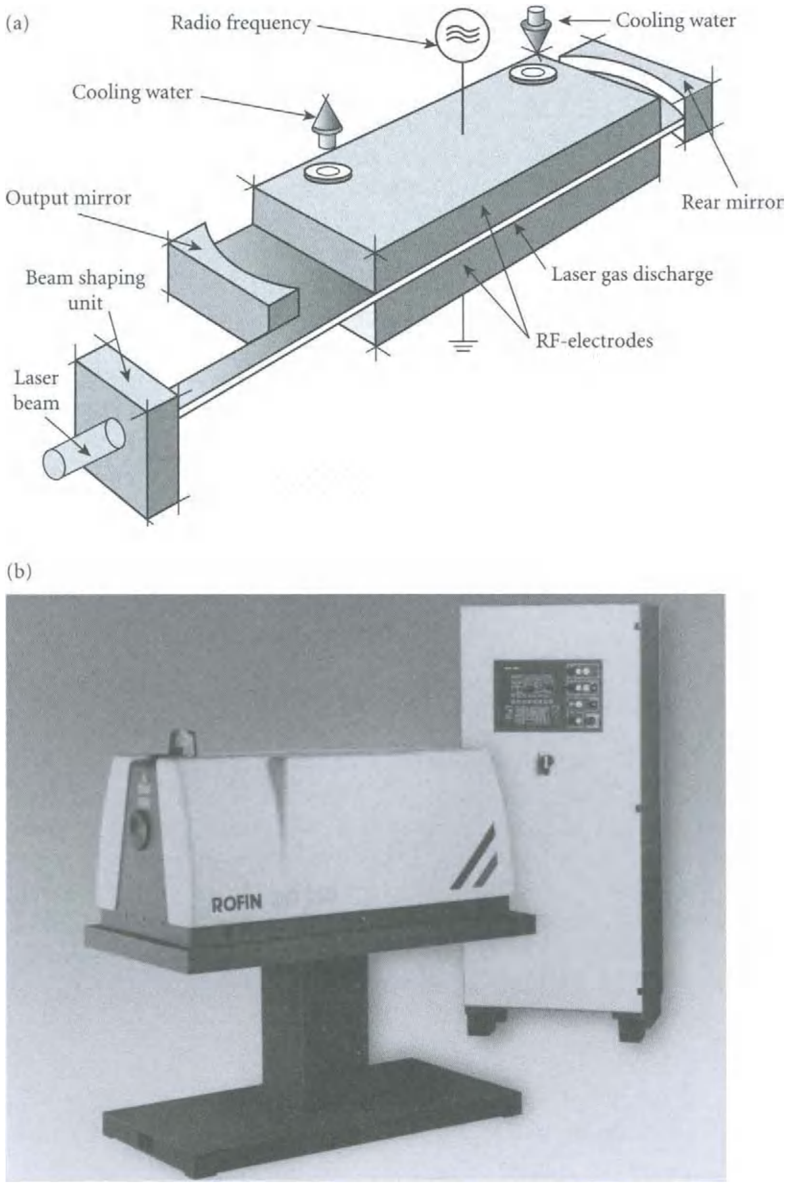

Figure 3.17 Diffusion-cooled CO_2 slab laser: (a) schematic; (b) Rofin DC 025. (Source: Friedrich Bachmann, Rofin, Hamburg, Germany)

Only pulsed output is possible from a TEA laser, since discharge instabilities are easily produced in the high pressure gas environment, which degrade the output power. The beam may be TEM_{00} or multimode, and is typically several square centimetres in cross-sectional area. By using very short discharge times, pulses of energy on the order of joules can be produced with a duration in the range tens of nanoseconds to microseconds. Repetition rates are limited to a few pulses per minute. Mode locking enables short (nanosecond) pulses of high peak power (1–50 MW) to be produced at a rate of 20–100 Hz.

TEA lasers have a small power supply and a lightweight laser head, and are used for marking – product coding of aluminium cans and plastic packages are popular applications.

Slow Axial Flow

The gas mixture used in slow axial flow (SAF) lasers contains a relatively high amount of helium to facilitate cooling, Table 3.1. The gas pressure is similar to that of a sealed unit. The optical cavity is constructed from glass tubes several centimetres in diameter. For a given temperature rise, the power generated is proportional to the tube length; long optical cavities are therefore necessary in high power units. The optical cavity generally consists of a totally reflecting spherical mirror, whose focal point is situated in the plane of a partially reflecting output coupler located at the opposite end of the cavity.

As the name suggests, gas flows relatively slowly in the SAF design, in an orientation parallel to the optical axis. Gas circulation allows contaminants generated in the discharge region (mainly carbon monoxide and oxides of nitrogen) to be removed. The low flow rate allows the laser gas to be heated quickly, which reduces start-up time, but the gas temperature must be kept below about 250°C to maintain gain in the resonator. Heat is conducted from the gas through the walls of the discharge tube, which may be cooled by air, oil or water; narrow tubes are therefore used to maximize cooling.

Excitation is normally achieved with a DC source of several tens of thousands of volts. DC is preferred since features such as cathode contamination and size, which require attention in sealed lasers, can be overcome by continuous gas circulation. Output power increases with increasing discharge current, up to a point at which the heating effect becomes significant. The optimum discharge current depends on the gas pressure and the tube diameter.

Since gas flow and light generation are coaxial, the beam propagates in the direction of the mean thermal gradients, and variations in gain are averaged out along the beam path, producing a stable beam mode. This construction, in combination with a stable mirror alignment and the limited tube diameter, enables a high quality TEM$_{00}$ beam to be generated. Two kilowatt CW units are available – a value that corresponds to a resonator length of about 3 metres, above which the cost of floor space makes the unit uneconomical to operate. (If the cavity is folded, the mechanical complexity is increased and it becomes difficult to obtain a good beam quality.) Relatively high energy pulses can be generated.

Because of the simplicity of the design, running and maintenance costs are low. Units with an output power in the range 150–750 W account for most sales. Slow axial flow CO$_2$ laser designs are ideal sources for fine cutting, scribing, precision drilling, and pulsed welding applications.

Fast Axial Flow

The output power of the axial flow laser can be increased by increasing the diameter of the optical cavity and raising the gas flow rate – features of the fast axial flow (FAF) design. Turbine blowers are used to circulate the gas mixture at high speed. (Roots blowers were used in early FAF designs; these were the source of many problems that initially harmed the reputation of this type of laser.) The gas composition is maintained by continuously adding a small amount of make-up gas into the resonator; this represents the gas consumption of the laser. Gas is cooled by passage through a heat exchanger containing deionized water (to avoid voltage imbalances).

The optical cavity of the FAF laser has many features in common with the SAF design. The resonator tube diameter is limited by mechanical and thermal distortions, as well as the generation of high order beam modes. In order to minimize the footprint, the resonator tubes are folded in various geometries with the use of mirrors; vertical zig-zag arrangements, superimposed vertical squares, an inclined triangle and an octagon have all been used in commercial designs. Each section has its own electrodes and gas ports in order to maintain a high flow rate. The radius of curvature of the back mirror is large (several metres). This enables power output to be increased, but leads to the production of modes other than the preferred TEM$_{00}$. Apertures can be used to limit the mode to TEM$_{00}$ with an attendant loss in power. Small adjustments in the curvature of the back mirror can be made to change the beam mode in some designs. A hemispherical cavity configuration produces a superior mode, but again at the expense of lower power. A solid coated zinc selenide output coupler (highly transparent to far infrared radiation) is normally used for a power output less than about 10 kW; higher values require an aerodynamic window.

Both DC and RF excitation are used in commercial FAF designs. The anode of a DC system is a cylinder located inside the tube in a coaxial geometry. The cathode is situated downstream at the end of the discharge section. The discharge is stabilized using orifices that generate shockwaves, which remove high density electron clusters. Rapid expansion of gas downstream of the orifice also has a cooling effect, which enables a higher power output to be achieved. In RF-excited units the electrodes are mounted outside the discharge tubes.

A stable low order beam mode ($0.4 < K < 0.75$) can be generated because of the gain-smoothing effect of turbulent gas flow. The output, which may be continuous or pulsed, is stable to within ±2% over periods of several hours. Pulsing is achieved mechanically in DC-excited designs. Pulse and super pulse operation are possible by electrical means with RF excitation, enabling a peak power 2–10 times that of the continuous value to be obtained. The folding geometry of the cavity determines the beam polarization: if the angle between the beam and the mirrors is close to 45°, then the perpendicular component is preferentially reflected, producing a state of linear polarization. A preferred state of polarization gives the beam specific material processing properties in different directions of travel.

FAF lasers are used in a wide range of material processing applications, including welding, cutting and surface treatment. Pulsed output is useful for initiating cuts, drilling, and perforating sheets. Commercial FAF units are limited to about 20 kW because high gas flow rates require complex blower technology, and high gas pressures lead to difficulties in maintaining a glow discharge. A schematic illustration of an FAF laser is shown in Fig. 3.10a, and a production laser shown in Fig. 3.10b.

Transverse Flow

A basic requirement for generating high power is the ability to excite a large volume of gas in a given time. This can be achieved by circulating the gas across a cavity of large cross-sectional area. Such designs are referred to as transverse flow (TF). This geometry has a number of advantages over the FAF design. Gas flow rates are typically one tenth those of fast axial flow designs, which reduces the requirements on the blowers, and reduces flow rate losses that lead to increased temperatures, loss of population inversion and reduced beam power. Pressure differentials are lower, and since gas resides in the discharge volume for a shorter time, more power per unit length of cavity can be generated, enabling considerably shorter cavities to be constructed.

A positive branch unstable cavity, constructed using one concave and one convex mirror (Fig. 3.7), is normally used in systems that produce output above 6 kW. The high cavity gain permits laser transitions despite the relatively high loss in the cavity. The beam is extracted (normally through an aerodynamic window) using an annular curved scraper mirror. The exclusive use of reflective optics is another factor that allows high values of power to be generated and extracted.

The axis of excitation is normally oriented perpendicular to both the gas flow and the optical axis. This geometry provides unimpeded gas flow and a short discharge path (typically around 5 cm), which enables a relatively low working voltage to be used – between 10 and 20% of fast axial flow designs. Both DC and RF excitation are suitable for TF designs. Direct current excitation uses a sophisticated segmented electrode to maintain a uniform discharge over the large electrode area, to reduce the possibility of arcing. In some designs the cathode is water cooled. Radio frequency excitation requires only two electrodes, which can be placed outside the discharge region. The discharge may be stabilized using a turbulence generator or by using an electron beam. The latter technique, in which a wide beam of high energy electrons assists the production of a uniform volume discharge, is expensive.

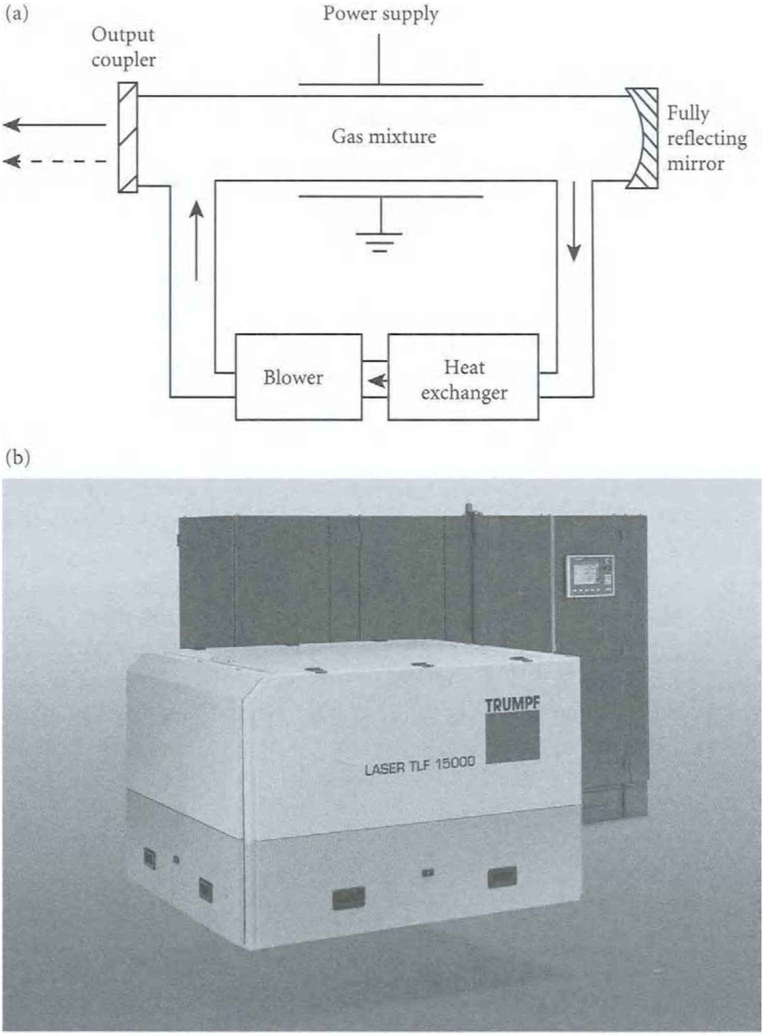

Figure 3.16 Fast axial flow CO$_2$ laser: (a) schematic; (b) Trumpf TLF 15000. (Source: Sven Ederer, Trumpf, Ditzingen, Germany)

Preionisation is necessary if the main discharge is to fill the laser volume. Cooling is via a heat exchanger containing deionised water.

The distribution of power in the beam depends on the geometry of the optical cavity and the method by which the beam is extracted. The output from an unstable cavity has a characteristic annular intensity distribution, generated by the annular scraper mirror. A stable cavity produces a multimode beam comprising a mixture of low order transverse modes because of its relatively high Fresnel number. Transverse discharge inhomogeneities can result in an asymmetric beam that is larger than one comprising low order stable modes, and which has a higher divergence (2–5 mrad). Relatively high M^2 values (>5) are common. High power stability is within ±2% and ±5% over minutes and hours, respectively.

In comparison with other laser designs, transverse flow lasers can be made relatively easily in modular, enabling designs to be scaled to high power outputs. The capital cost per kW is lower, and the compact design results in a smaller footprint. The use of a metal container and all-reflecting optics

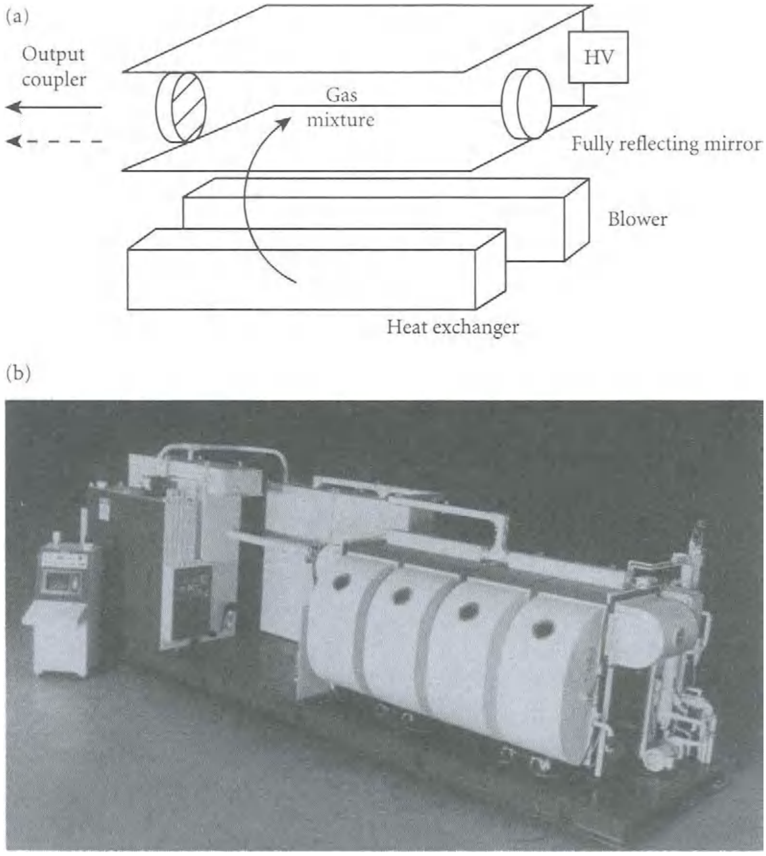

Figure 3.19 Transverse flow CO_2 laser: (a) schematic, (b) UTIL (now Prima Industrie) 25 kW. (Source: Robert Murray, Prima Industrie, East Hartford, CT, USA.)

allows the optical cavity to be rugged in design. Gas usage is lower than a fast axial flow laser, and lower operating voltages can be used than in DC designs. However, pulsing, other than by mechanical means, is difficult, and the beam mode is of lower quality than axial flow designs. Such high power lasers are commonly used for material processing operations such as thick section welding and large area surface treatment. A schematic illustration of a TF laser is shown in Fig. 3.19a and a production laser shown in Fig. 3.19b.

Gas Dynamic

Although the gas dynamic carbon dioxide laser is not a commercial design, it is of interest for material processing since continuous power levels to 100 kW have been produced. The population inversion is created by thermodynamic means, rather than electrical. A fuel is mixed with an oxidizer to yield combustion products suitable for laser transitions; combustion of CO and CH_4 with O_2 and N_2 yields CO_2, N_2 and H_2O. At high temperatures, most of the energy is stored as vibrational excitation in nitrogen molecules. As the gas expands through a supersonic nozzle, this energy is rapidly transferred to CO_2 molecules through collisions, exciting them to the (00^01) level to create a population inversion with the (10^00) level. Certain high energy states are momentarily frozen, creating a non-equilibrium condition that promotes the population inversion.

Carbon Monoxide

The active medium in the carbon monoxide (CO) laser is CO gas in a mixture of helium and nitrogen, with small amounts of xenon. The gas ratio by volume lies around 1:20:1 (CO:He:N_2), maintained at an operating pressure of about 100 mbar in CW mode and higher values in TEA designs. Nitrogen and helium play similar roles to those in the carbon dioxide laser: efficient excitation and cooling, respectively. Xenon is added to change the average electron energy, thereby increasing the fraction of electrical power transferred to excitation of vibrational levels, which increases the power generation efficiency by about 50%. A small amount of oxygen also enhances performance.

The diatomic CO molecule has only a single vibrational mode, in contrast to the three vibrational modes of the carbon dioxide molecule. The quantum efficiency is close to 100% because the lower laser level of a given transition can serve as the upper laser level of a subsequent transition, which means that light can be produced from several pairs of levels to support a population inversion. Radiation therefore occurs on a range of discrete infrared lines, with wavelengths between 5.2 and 6.2 µm.

The active medium must be cooled to cryogenic temperatures below 77 K to maintain a population inversion. This may be achieved by conduction or aerodynamic cooling. Low power lasers (below 100 W) are cooled by gases and circulating fluids. Higher power designs are usually cooled in a liquid nitrogen or Freon® heat exchanger. (Freon is a registered trademark belonging to E.I. du Pont de Nemours & Company (DuPont).) Cooling can also be achieved by adiabatic expansion in a supersonic nozzle. After power has been extracted from the resonator, the laser gas is recompressed by a diffuser and a pumping system.

Commercial units are often based on modified CO_2 resonator designs – the changes that are required include substitution of appropriate optics, insertion of the correct gas mix and the addition of cooling equipment. The cavity can take the form of a tube or waveguide, which can be sealed or transport flowing gas. A solid output window with a low absorption coating is located at one end of the cavity. The resonator design is scalable to provide high power levels. Low power designs are based on large area slab waveguides: a large bore refractory ceramic tube 1 m in length and 25 mm in diameter can produce about 20 W, which can be increased to 300 W by scaling the dimensions three-fold. Excitation is electrical, achieved by DC and RF means. A wall plug efficiency close to 25% is possible (around twice that of an equivalent CO_2 laser) because of the high quantum efficiency, providing that the means of cooling is energy efficient. The beam quality (M^2) typically lies between 2 and 2.5.

In comparison with the carbon dioxide laser, the shorter wavelength of CO laser light possesses a number of advantages for material processing. Short wavelength light is absorbed more readily by metals and ceramics and so a lower power level can be used for processes that involve heating and melting. The beam can be focused to a spot of smaller diameter, giving a higher power density that facilitates keyhole formation in penetration welding, and piercing to initiate cutting. The plasma generated when welding metals is white (in contrast to the blue plasma generated through metal ionization during CO_2 laser welding), which means that a larger fraction of the beam is transmitted through the plasma to the workpiece. Transmissive optical materials are available with a high damage threshold, and there is greater potential for fibre optic beam delivery.

The development of CO lasers has been hindered by two factors: the need for cooling to operate efficiently and instabilities in the gas mixture. CO dissociates into C and O as a result of the electrical discharge, necessitating the use of a flowing gas mixture to maintain composition during long-term operation.

Hydrogen Fluoride

The hydrogen fluoride (HF) laser is a chemical laser that combines heated hydrogen (produced in a combustion chamber similar to a rocket engine) with fluorine gas (produced by thermal decomposition of compounds such as sulphur hexafluoride) to form excited HF molecules. Far infrared emission occurs on lines between 2600 and 2900 nm in wavelength, the exact line depending on the chemical composition of the reacting gases.

Hydrogen fluoride lasers are under consideration for space-based missile defence systems, although the emitted wavelengths transmit poorly through the lower regions of the atmosphere since they are absorbed by water. (Propagation through upper regions and in space is superior.) Interest lies in the fact that the reactants used can be stored for long periods of time, and waste products and heat can be exhausted into space. Pulsed power levels in the megawatt scale have been generated. Systems are being designed that can be operated and maintained from the ground.

Deuterium Fluoride

The deuterium fluoride (DF) laser uses a chemical reaction between atomic fluorine and deuterium to produce the active medium. It is chemically the same as the hydrogen fluoride laser; however, the increased mass of heavy deuterium shifts the output lines to between 3500 and 4000 nm, which is superior for transmission through the lower atmosphere.

A megawatt-class CW chemical laser, known as MIRACL (Mid-Infrared Advanced Chemical Laser), produces power distributed among ten lasing lines between 3600 and 4200 nm. Beam shaping optics have been used to form a 14 cm square beam that can disable a satellite the size of a refrigerator located 200 miles above the earth's surface. Such military applications have been a significant driving force in the development of chemical lasers.

Hydrogen Chloride

Light can also be produced from excited hydrogen chloride (HCl). This was the first chemical laser to be demonstrated. HCl can be generated in a mixture of chlorine and hydrogen through pulsed photodissociation of chlorine using a flashlamp, or by the reaction of nitric oxide (NO) with ClO_2. Output is on lines between 3500 and 4000 nm in wavelength.

Nitrogen

Nitrogen gas, at a pressure of between 0.01 and 1 bar, is the active medium in the nitrogen laser. The gas is normally circulated, but low repetition rate pulsed designs can be sealed.

Nitrogen lasers generate light through transitions between both electronic and vibrational energy levels. The stimulated gain is high, which means that only one mirror needs to be used; feedback is not required for laser action. The lifetime of the upper level is short, while that of the lower level is long – CW operation is therefore not possible, but pulsed operation is. Pulse widths are short, because as soon as the laser transitions begin, the population of the terminal state increases rapidly, and after a few nanoseconds the population inversion is reduced to a level at which laser action cannot be sustained (self-termination).

The optical cavity is similar to that of a TEA CO_2 laser. The active medium is excited using a fast high voltage discharge between electrodes placed transversely to the optical axis. The gas medium is cooled by passing through a heat exchanger, which may use circulating air.

Pulsed ultraviolet light of wavelength 337.1 nm is generated, in the form of a rectangular beam with dimensions between 2 × 3 and 6 × 30 mm. The pulse duration is on the order of nanoseconds and is produced at frequencies to 1 kHz, with a pulse energy limited to tens of millijoules, and an average power of several hundred milliwatts.

Nitrogen lasers were initially used as excitation sources for pulsed dye lasers, but because of their short wavelength they can also be used in non-linear spectroscopy, non-destructive testing and Raman scattering. Material processing on a microscopic scale can be performed. Nitrogen lasers show potential for laser-assisted chemical vapour deposition because of the focusability of the beam, enabling sharp, even deposits to be produced.

Organic

Organic molecular gas lasers emit on lines of wavelength between about 25 µm and 2 mm. At the short wavelength end of the range, light is generated from vibrational–rotational transitions. Purely rotational transitions are involved in longer wavelength transitions. The active media possess a permanent dipole moment. Alcohols and other carbon-based compounds such as CH_3OH, $C_2H_2F_2$ and CD_3OD are commonly used. Optical pumping is preferred, since it permits precise selection of the initial excited state. This is normally achieved using an external CO_2 or N_2O laser, which is tuned to emit on a single line around 10 µm in wavelength. They are primarily used in research (to diagnose fusion plasmas), astronomy and in studies of semiconductor materials.

IONS

Light is generated in ionised gases through electronic transitions. Since the excitation energy of an ion is larger than a neutral atom, ionised gas lasers produce light of shorter wavelength, in the range between mid-ultraviolet and visible.

The gas is present in a mixture with buffer gases such as neon or helium or both (depending on the emission line or lines required), at a pressure below atmospheric. The cavity design is similar for all types of gas ion laser. The discharge tube is normally made from a ceramic such as beryllia in lower power lasers (typically a few millimetres in diameter), but may be made from graphite or tungsten discs surrounded by quartz in higher power designs. Excitation is via an electrical arc discharge operated at a relatively low voltage and high current. The current required to create a population inversion is high – larger than that used in atomic gas lasers – because atoms must first be ionised before further collisions with electrons can excite them to the higher energy levels required for laser transitions. The overall efficiency is therefore relatively low, less than 0.1%. The mirrors bounding the cavity may be spherical or a combination of spherical and concave. A solid window is attached to one end of the tube, mounted at the Brewster angle to minimise reflection.

The average beam power obtained is on levels between milliwatts and watts. Beam quality is high, and has a narrow bandwidth. Output is CW, but pulses can be produced using mode locking. The cost of a unit is on the order of thousands of dollars.

Argon

Argon ion lasers excited by an electric discharge emit on several lines in the range yellow–ultraviolet. Emission of green and blue wavelengths is the most prominent. Power levels on the order of tens of watts can be obtained.

Argon ion lasers are used in light shows, interferometry, fluorescence excitation, Raman spectroscopy, forensic medicine, research, printing (exposing plates for printing presses) and holography. They are also effective optical pumping sources for other lasers. The most common material processing applications include etching of semiconductors to form optical waveguides, and microscopic medical procedures involving ophthalmology and minimally invasive surgery.

Krypton

The krypton ion laser emits on a range of lines for the wavelength range from ultraviolet to infrared (350–700 nm). The main line is red, on which several watts can be obtained. The output is less than the argon ion laser because the gain in the resonator is lower. The uses of krypton ion laser output are similar to those of the argon ion laser.

Argon–Krypton

Lasers using mixtures of argon and krypton emit strongly in the red and blue regions, with a beam power on the order of watts. Applications are similar to those of the individual lasers.

Xenon

The xenon ion (Xe^{3+}) laser produces pulsed green and ultraviolet light. It is used for minimally invasive surgery since green light is absorbed well by tissue containing red blood cells.

Copper Vapour

Copper, gold, and elements in the same and adjacent columns of the periodic table can be used to produce active media in the form of ionized metal vapours. Metal vapour lasers emit visible light as a result of transitions between low-lying energy levels. In the copper vapour type, the active medium is formed at the anode of a plasma tube containing elemental copper and an inert buffer gas, by passing an electric current using a high voltage switch. Transitions between the upper energy states result in the emission of yellow and green light. The lower laser level is the ground state, and so light can only be generated for a short time before the population inversion is destroyed. The laser is therefore operated in pulsed mode. It takes about 25 µs to deactivate the terminal level (after which energy transitions can recommence), which limits the maximum pulse duration and repetition rate.

The plasma tube is typically 10–80 mm in diameter, bounded by a converging mirror and a plane output coupler. Both stable and unstable cavity designs are used. The cavity is easily scaled in power, while retaining a good beam mode, because of the high gain. Metal vapour is formed in a neon atmosphere at a pressure between 30 and 70 mbar. The operating temperature is high (between 1300 and 1600°C), which is a factor that has limited the development of commercial units.

Output is in the form of short pulses, tens of nanoseconds in duration, with a high repetition rate, up to 20 kHz, a relatively high average power (over 100 W), a peak power of several hundred kilowatts, and a pulse energy of up to 20 mJ. High temperature operation favours the production of yellow light. Frequency-doubling provides two ultraviolet wavelengths: 255.3 and 289.1 nm. (Applications then overlap those traditionally associated with excimer lasers – KrF lasers operate at 248 nm. However, the pulse repetition rates obtainable from the copper vapour laser are around a thousand times higher, resulting in significantly greater material removal rates in drilling applications, for example.)

Short wavelength light can be focused to a small, high intensity spot, ideal for micromachining of ceramics, reflective metals (e.g. aluminium, copper and brass), and polymers. Cuts with a typical kerf width of 2 µm can be made. Holes with an aspect ratio of 50 can be drilled.

Gold Vapour

The gold vapour laser operates on similar principles to the copper vapour laser. Red light is produced in pulses with an average power up to 10 W. The laser initially found similar applications to the copper vapour type, but it is relatively expensive since red light can now be produced from other sources more cheaply and conveniently.

Helium–Cadmium

The helium–cadmium (He–Cd) laser is one of a family of sources that use a metal with a low vaporization temperature as the active medium. Cadmium is heated with a filament to produce a vapour that is mixed with helium. Helium is ionized and excited in a pulsed discharge. Energy is then transferred from excited He to a neutral Cd atom by collision, causing the Cd atom to be ionized and excited further.

Light is produced by electronic transitions between the excited *ionic* state and the *ionic* ground state. The strongest output is on lines in the blue and ultraviolet ranges. Weaker red and green light can also be produced. Atoms remain in the excited state for only a short time, returning to the ground state where they accumulate, quickly removing the population inversion needed for laser action.

The He–Cd laser operates in pulsed mode, with an average power on the order of milliwatts. (The power output is often quoted in terms of an average CW.) The active medium has a high gain compared with similar lasers. TEM$_{00}$ and multimode beams can be produced.

The helium–cadmium laser is used in Raman spectroscopy, to fabricate holographic gratings, and in photochemical material processing techniques such as stereolithography.

Helium–Selenium

The helium–selenium (He–Se) laser operates on similar principles to the He–Cd laser. Transitions between excited states of selenium produce radiation in the visible spectrum, between blue and red. Average power outputs on the order of tens of milliwatts can be obtained, but the laser is not used extensively in material processing because alternative lasers that are cheaper can produce light in this range of wavelength.

X-ray

X-rays occupy the wavelength region of the electromagnetic spectrum between roughly 0.01 and 10 nm. They are generated in the X-ray laser by excitation of a polished palladium or titanium target with a high energy light pulse around one nanosecond in length. Electrons are stripped from titanium and palladium atoms, producing plasma that contains excited ions with similar stable electron configurations to neon and nickel, respectively. Decay of high numbers of ions produces powerful 'soft' X-rays with a wavelength slightly longer than that used in medical imaging.

Coherent radiation of short wavelength and short pulse duration is suitable for applications in biology, chemistry and materials science. The X-ray laser was developed during the *Strategic Defense Initiative* as a means of destroying incoming missiles. Civilian alternatives lie in the manufacture of nanometre-scale structures required in the fields of quantum electronics, and the construction of nanometre-scale robots (nanobots).

EXCIMER

The active medium in an excimer laser consists of a mixture of gases: a rare gas (1–9%); a halogen (0.05–0.3%); and an inert buffer gas (90–99%). The total gas pressure is around six times atmospheric. The gas mixture is circulated rapidly (up to 50 m s^{-1}) and reprocessed to maintain the desired composition.

It is cooled in a heat exchanger and filtered, since changes in temperature and gas composition create difficulties in maintaining a stable beam mode. The laser gas slowly degrades – halogen is depleted and impurities including HF, CF_4, SiF_4 and CO_2 form – resulting in a gradual reduction of gain.

A plane-parallel optical cavity is used, made of materials such as aluminium, fluorocarbons and ultra pure ceramics that are resistant to corrosive halogens. A thin layer of aluminium nitride may be chemically deposited on an extruded aluminium chamber to enhance protection. The two windows bounding the cavity are typically made from polished magnesium fluoride; one has a highly reflective aluminium or dielectric coating on its rear surface, the other acts as the output coupler. The aperture has a cross-sectional area between 1 and 5 cm². Gain in the cavity is high, and so adequate feedback can be achieved with a resonator length of only about 100 cm using an output coupler of reflectivity 5–10%. The mirrors may be placed outside the optical cavity in order to avoid corrosion problems. Low beam divergence and good focusability can be achieved through the use of an unstable resonator.

The active medium is excited by a high voltage discharge applied orthogonal to the axis of the optical cavity and the gas circulation, in a similar manner to that in a TEA CO_2 laser. The electrodes are normally rectangular with a spacing of about 25 mm. Large cross-section discharges require a sufficient concentrated electron density for optimum ionization; this can be achieved by preionization using X-ray, ultraviolet and electron beam sources. The discharge is operated at high peak currents with short current rise times, which places considerable loads on the switches and high voltage capacitors – thyratrons are used as high voltage switches. Excitation typically involves a 50–100 ns duration pulse with a voltage of 35–50 kV.

In commercial sources, light is generated in the form of ultraviolet pulses, with a wavelength in the range 150–350 nm, via transitions between electronic and vibrational energy levels. Since the spectral gain bandwidth is broad (>100 cm^{-1}), many transverse and longitudinal modes can oscillate simultaneously in a stable plane-parallel resonator. The beam quality is relatively low ($M^2 \approx 100$) but can be improved by an order of magnitude through the use of unstable resonator optics, at the expense of a reduction in power. A rectangular beam cross-section is common, ranging between 2 to 4 and 25 to 40 mm, with an intensity distribution that is approximately Gaussian in the shorter dimension but flatter in the longer dimension. The beam divergence is typically below 4 mrad. Beam homogenizers (arrays of lenses) are used to split the beam into segments which are superimposed in the aperture plane. The number of materials that transmit efficiently at ultraviolet wavelengths is limited; fused silica, fused quartz and crystalline halides are suitable for wavelengths above about 375 nm, while sapphire and crystalline fluorides of lithium, magnesium, calcium and barium are more appropriate for shorter wavelengths.

The precise nature of the output depends on the active medium. Light pulses have the following characteristics: energy in the range millijoules to joules; average power up to several hundred watts; repetition rates between about 20 and 1000 Hz; and pulse durations from a few to a hundred nanoseconds, giving peak power values up to 60 MW. Operational limits are determined by the rate of high speed switching (the thyratron) and the resonator length. The maximum gas flow velocity determines the maximum pulse frequency obtainable. Long pulses can be obtained by superimposing the output from several lasers. The conventional technique for reducing pulse length – Q-switching – cannot be used because of the lack of a suitable saturable absorber. Mode locking cannot be used either, since it relies on maintaining gain in the cavity for a substantial number of round trips – this cannot occur in excimer lasers because of the small number of passes in the high gain medium. Properties of the most common commercial excimer lasers – those based on argon fluoride, krypton fluoride, xenon chloride, and increasingly fluorine – are summarized in Table B.1 (Appendix B). Brief descriptions of the individual lasers follow here.

Short wavelength ultraviolet light has three main advantages for material processing: high absorption by many engineering materials; high spatial resolution; and high photon energy (similar to that of chemical bonds). Ultraviolet light can therefore be focused to a small spot size and located with high accuracy to process a wide range of materials, including metals, ceramics and polymers. A short wavelength also provides opportunities for photochemical material processing, in addition to the thermal processing mechanisms characteristic of infrared lasers. The short pulse width and high peak power reduce the heat affected zone in materials. Since the transparency of the plasma is proportional to $1/\lambda^2$, where λ is the wavelength, plasma shielding is less of a problem than with infrared laser light.

Excimer lasers have a wall plug efficiency of 1–2.5%. The running cost of an excimer laser is high in comparison with solid state and CO_2 lasers. The capital cost is also relatively high – from $30 000 to $200 000 (around $1000 per watt). Excimer lasers initially replaced nitrogen lasers for pumping tuneable dye lasers for spectroscopic studies, and later competed with Nd:YAG lasers for pumping higher

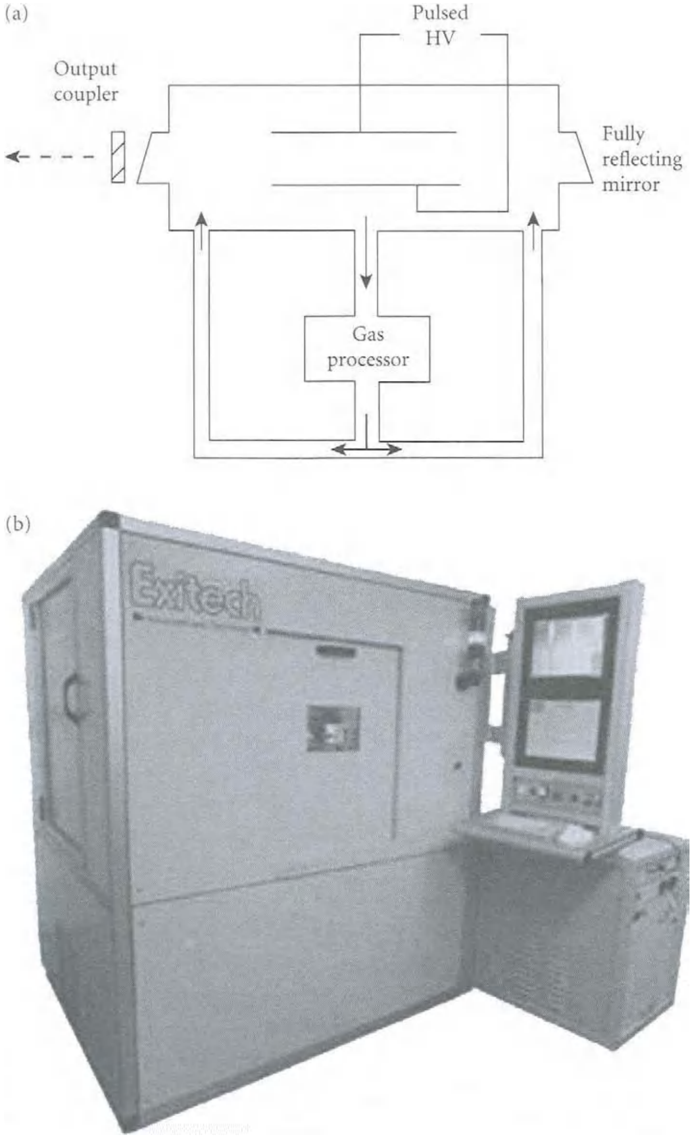

Figure 3.20 Excimer laser: (a) schematic; (b) Exitech M5000 micromachining tool. (Source: Adrian Baughan, Exitech Ltd, Oxford, UK)

power lasers. They are now used extensively in corrective eye surgery, microlithography, micromachining, marking, annealing, doping, vapour deposition, and other surface modification techniques with a wide range of metals, ceramics and polymers. A schematic illustration of an excimer laser is shown in Fig. 3.20a, and a production laser micromachining tool shown in Fig. 3.20b.

Argon Fluoride

The short wavelength of the argon fluoride excimer laser has resulted in it becoming the source of choice for corneal surgery including photorefractive keratectomy (PRK) and laser *in-situ* keratomileusis (Fig. 1.4, Chapter 1), as well as lithography.

Krypton Fluoride

The krypton fluoride laser has the highest intrinsic efficiency of excimer lasers, and found many applications shortly after its invention. Today its main application is in fine scale lithography.

Xenon Chloride

Xenon chloride is the optimum medium for discharge excitation, enabling high power pulses (1 kW average) of relatively long duration (150 ns) to be produced. The wall plug efficiency of 2.5% is the highest of the excimer laser family. Fused silica, fused quartz and several crystalline halides are used in beam delivery optics. Drilling and other machining operations are typical high power applications, while microlithography is a major application of low average power units.

Xenon Fluoride

The xenon fluoride laser was investigated for early defence-related applications because the relatively long wavelength (350 nm) is transmitted well in the atmosphere.

Fluorine

The fluorine laser produces the shortest wavelength of commercial excimer lasers, and provides relatively high output power. It is being developed for future microlithography applications, particularly with polymers and glasses, photomask and mask development, photochemistry and spectroscopy and for testing of optics, coatings and metrology equipment.

Xenon

Xenon was the active medium in the first excimer laser to be demonstrated, but mixtures of rare gases and halides have proved to be more appropriate for industrial units.

Xenon Bromide

Xenon bromide formed the active medium of the first rare gas–halide excimer laser to be demonstrated. It is relatively inefficient as a laser, but is a good emitter of fluorescence, and so is a popular choice for lamps.

LIQUIDS

The active medium in most liquid lasers is a complex organic dye. Dye lasers operate on a fundamental four-level system, involving transitions between many split energy states created by vibration of the molecule.

Dye lasers are optically excited, using a flashlamp or another laser of shorter wavelength than the desired output. Xenon flashlamps arranged in a linear or coaxial geometry give a wall plug efficiency of up to 1%. Dye laser excitation, using nitrogen, excimer, copper vapour or frequency-multiplied Nd:YAG sources, produce light with 5–25% pumping efficiency. Argon or krypton ion lasers give around 10–20% conversion of light to pump energy. Dye lasers are high gain, requiring minimal oscillation to build up the beam, but must be cooled by a circulating medium.

Dye lasers can be tuned to emit at a variety of wavelengths in the range 300–1000 nm, by changing the angle of the grating used as the output coupler. They operate principally in pulsed mode, although models pumped using a CW ion laser can operate in CW mode. The pulse length depends principally on the type of excitation source. Flashlamp pumped dyes produce pulses of length 20–4000 ns, energy 0.05–50 J, with a repetition rate of 0.05–50 Hz, giving a peak power of several hundred kW and an average power in the range 0.25–50 W. Laser-pumped dyes typically produce pulses of length 5–30 ns, up to 10 kHz, with an average power 0.05–15 W, and peak pulse powers on the order of megawatts. The pulse characteristics are determined by the dye used, and can be modified by mode locking or cavity dumping. Frequency doubling and Raman shifting extend the range of operation even further.

Colour variability is important when treating materials whose absorptivity depends on wavelength. For example, blood does not absorb red light significantly, and so a different wavelength must be used for surgical procedures in blood-rich tissue.

Rhodamine

The chemical formula of Rhodamine B is $C_{28}H_{31}ClN_2O_3$. The energy-level structure of an organic dye molecule is correspondingly complex. The flashlamp-pumped Rhodamine 6G laser has a tuning range between 570 and 660 nm. It is used in cosmetic procedures to remove leg and spider veins, port wine stains and scars. Typical beam characteristics are: wavelength 585, 590, 595, 600 nm; pulse length 1.5 μs and energy density 5–25 J cm^{-2}.

Coumarin

Coumarin has a chemical formula $C_9H_6O_2$, and is the dye used as the active medium in lasers intended for ablation processes. A flashlamp-pumped Coumarin dye laser produces a wavelength of 504 nm (green). During laser lithotripsy this type of beam has a large effect on a kidney stone and a small effect on the ureteral wall. When the stone absorbs the laser light, a small amount of heat is generated, which creates a cavitation bubble. The expansion and contraction of this bubble create acoustic waves, which pass into the stone, resulting in fragmentation.

SOLIDS

Nd:YAG

The active medium in the Nd:YAG laser is a solid host material of yttrium aluminium garnet (YAG) doped with neodymium ions (Nd^{3+}). The host is a synthetic crystal with a garnet-like structure, and the chemical formula $Y_3Al_5O_{12}$. Neodymium ions take the place of yttrium ions in the garnet lattice – they are roughly the same size. Ions are present at concentrations around 1% by weight, which corresponds to a concentration of about 10^{20} ions cm^{-3}. The optimum concentration for continuous wave operation is around 0.8%, whereas 1.2% is more suitable for pulsed operation. The neodymium ion contains a partially filled 4*f* subshell, which provides the electrons for the laser transitions. The 4*f* subshell is shielded by filled 5s and 5p subshells. The active medium is in the form of a rod, or one of the novel geometries described below. The main advantage of YAG compared with other laser materials is its good thermal stability.

Light is generated through transitions between energy levels of the neodymium ion. The laser is based on four-level operation, illustrated in Fig. 3.4: a ground level; absorption bands; an upper laser level, and a lower laser level. Excitation occurs by absorption of visible and infrared light at wavelengths of 730 and 800 nm, respectively. Ions are raised from the ground level, $^4I_{9/2}$, to the $^4S_{3/2}$ and $^4F_{7/2}$ (730 nm) and $^4F_{5/2}$ and $^2H_{9/2}$ (800 nm) absorption bands, with a quantum efficiency of up to 50%. Once in the higher energy level they undergo non-radiative relaxation (with the generation of heat) to a metastable upper laser level, $^4F_{3/2}$. The lower laser level is $^4I_{11/2}$, which is normally unpopulated at normal temperatures. It is therefore relatively easy to obtain a population inversion, resulting in a relatively low threshold for laser action. An excited ion that drops to the lower laser level emits a photon of wavelength 1064 nm. The lower laser level is depopulated by thermal transitions to the host, causing further heating of the YAG rod.

The optical cavity of lamp-pumped designs normally takes the form of an Nd:YAG rod. Rods are typically 8–10 mm in diameter and up to 200 mm in length. They are expensive, since they must be machined from boules that can take up to eight weeks to grow. Such a rod is capable of producing about 750 W of power, and so multiple rods are used in higher power units. A long rod produces a beam of low divergence, whereas a short rod possesses good mechanical stability and can be packaged easily. Rods of large diameter have a high energy conversion efficiency; rods of small diameter have low divergence. Compromises in the dimensions of the rod must therefore be made in commercial lasers. The optical cavity must be designed to compensate for thermal lensing of the rod caused by uneven heating, which limits scaling of power. A fully reflecting mirror is located at one end of the rod, and a partially reflecting output coupler at the other. The gain in a solid rod is normally considerably higher than a gas laser, and so cavity mirrors with lower reflectivity can be used. Dielectric mirrors feature in high power lasers, with gold-coated metallic mirrors being used in lower power lasers. An optical cavity based on rods may be arranged in stable or unstable configurations. A low order mode beam with restricted power is generated in a stable cavity. An unstable cavity can be constructed by using similar mirror designs to those in CO_2 lasers; larger amounts of power may then be generated at the expense of a reduction in beam quality and efficiency. However, the focal plane moves with changes in output power, which must be compensated for by using adaptive optics.

Excitation is produced by flashlamps, arc lamps or semiconductor lasers. Only lamp pumping is considered in this section – diode laser pumping is described later. Linear flashlamps may be arranged in various geometries in hollow reflective containers. Lamps may be placed next to the rod in a close-coupling geometry. Alternatively, the lamp and the laser rod may be placed at the two foci of an ellipse in order to maximize excitation. High power oscillators may be surrounded by arrays of flashlamps. For long pulse lengths (greater than 1 ms), the power supply current is stabilized at the required value, and the pulse length is determined by the time between switch on and switch off. Shorter pulse lengths use capacitor discharging techniques.

High power cavity designs are often based on the oscillator–amplifier principle. The oscillator is a conventional laser, but the amplifier is a rod without the feedback elements, which is pumped by a separate lamp. The amplifier sections do not generate light, but store energy when excited. As the beam from the oscillator passes through the amplifier section, much of the energy is extracted in the excited state. The arrangement of several rods in one resonator is the most advantageous design for multikilowatt units, since the power can be scaled to high levels without losing beam quality.

Around 50% of the electrical power consumed is dissipated as heat inside the rod. Convective air cooling is used in low power units, whereas in higher power designs deionized water flows through an annular transparent cooling jacket between the rod and the lamp. The removal of waste heat becomes a major concern when the continuous power of an Nd:YAG laser exceeds about 2 kW. Cooling induces a parabolic temperature gradient within the rod, which then acts as a thermal lens. (The refractive index of the rod depends on temperature and internal stress.)

The beam quality lies in the range 20–100 (M^2) for stable resonator modes from rod lasers. Single transverse mode operation can be obtained by inserting apertures that limit the power. The value of M^2 increases with an increase in power because heating introduces changes in the refractive index of the rod, and the effect of imperfections in the rod on optical behaviour increases. The transverse beam mode is often complex, and is difficult to describe in mathematical terms using the TEM notation. A more common measure of quality for such lasers is the beam parameter product (the product of the beam waist diameter and half the divergence angle), measured in mm mrad.

Crystals of lithium iodate ($LiIO_3$) and lithium triborate (LiB_3O_5) can be inserted into the optical path to multiply the frequency of Nd:YAG laser light to generate harmonics. (The crystal only interacts with light polarized in a certain direction.) Thus the output wavelength can be halved to produce green light (532 nm), and divided by three to give ultraviolet light (355 nm).

Three temporal operating modes are possible: continuous wave; repetitive pulsing; and Q-switched pulsing. Multikilowatt power levels are available in CW operation. However, Nd:YAG lasers have traditionally been manufactured to take advantage of the ability of the YAG crystal to produce very high peak powers in very short duration pulses. The pulse length in a multiple element lamp-pumped laser is fixed by the length of the flashlamp pulse, which is typically on the order of milliseconds or microseconds. The pulse energy from such lasers is about 150 J, with pulse lengths up to 10 ms, and pulse repetition rates up to 50 Hz. The corresponding characteristics of single element units are: pulse energy up to 100 J; 0.5 ms pulse length; repetition rates up to 500 Hz; and a peak power up to 50 kW. As the repetition rate increases, the peak power available decreases, since excess heat must be removed. Q-switching enables 50 MW to be produced in a pulse of duration 100 ns.

Since Nd:YAG lasers can be operated in both continuous and pulsed mode, they possess flexibility for a wide range of material processing applications. The power available from CW units provides competition with CO_2 lasers in a variety of welding applications. Pulses of short duration and high peak power are particularly suitable for drilling applications. Frequency-doubled green light finds uses in material processing, particularly for machining colour-sensitive materials such as nitrides and polyimides. Ultraviolet frequency-tripled light competes with excimer output, and is finding applications in micromachining, marking polymers and glass, as well as in rapid manufacturing systems. The availability of fiberoptic beam delivery extends the range of application to complex geometry processing. The main disadvantages of the Nd:YAG laser, compared with the CO_2 laser, are: limited output power; low wall plug efficiency; and poorer beam quality. A schematic illustration of a lamp-pumped solid state laser is shown in Fig. 5.21a, and a production laser shown in Fig. 5.21b.

Nd:glass

Two families of glass are suitable hosts for neodymium ions: silicates, from which light of wavelength 1061–1062 nm can be generated, and phosphates that operate at 1054 nm. Glasses, which are relatively cheap, can be produced in larger sizes than YAG, and with a greater selection of geometries. Longer rods of high purity optically uniform glass enable higher average power levels to be achieved. Glasses can also be doped to higher concentrations than YAG, with good uniformity, which allows more energy to be stored, so that short high power pulses can be produced. However, the thermal conductivity of glass is lower than that of YAG, and so adequate cooling is required to avoid distortion caused by thermal heating. Phosphate-based glasses exhibit less optical distortion, but are less resistant to thermal fracture.

In comparison with the crystalline nature of YAG, glass is amorphous, which means that the line width of the neodymium ion transition is significantly broader; hundreds of axial modes operate

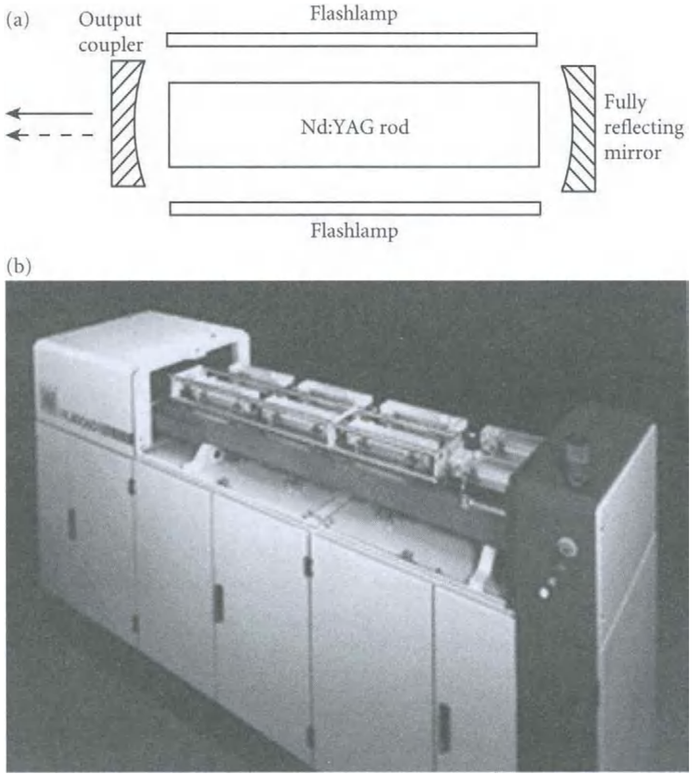

Figure 3.21 Lamp pumped Nd:YAG laser: (a) schematic; (b) HAAS 4 kW 4006D. (Source: Stan Edison, Trumpf, Ditzingen, Germany)

simultaneously. This leads to a higher lasing threshold, even though more energy can be stored and released in higher energy pulses.

Flashlamps are used to excite Nd:glass lasers. Optical distortion caused by thermal loading limits the output available from the rod: the laser can only be operated in pulsed mode. Nd:glass laser performance is normally limited to low duty cycle pulse repetition rates, around one per second.

Three operating regimes can be defined for Nd:glass lasers: normal pulsed mode (pulse length 1–10 ms); Q-switched operation (pulse length on the order of tens of nanoseconds); and picosecond pulse length. To overcome the repetition rate limitation, manufacturers have resorted to methods such as extracting the energy from both ends of the rod. In Q-switched operation, the output energy of an Nd:glass laser is comparable with that of a ruby laser (described below), with similar pulse durations.

Nd:glass lasers produce spiked pulsed output, which is ideal for metal drilling applications. They are also used for spot welding and drilling of deep holes. Frequency-doubled output (532 nm) is also used in scientific research.

Ruby

The active medium in the ruby laser is a single-crystal host of sapphire (Al_2O_3), doped with small amounts (0.01–0.5%) of chromium ions (Cr^{3+}). The ion contains three electrons in the partially filled 3d shell, which gives ruby its characteristic pink colour, and provides the electrons for laser excitation.

The low concentration ensures that the chromium ions are well separated, reducing the likelihood of interaction, which would lead to line broadening. Ruby has good thermal properties, and is unlikely to suffer fracture, particularly when water cooled.

The ruby laser operates on a three-level basis, illustrated in Fig. 5.3: a ground level (the lower laser level), absorption bands and an upper laser level. Since the terminal state of laser action is the ground level, which is normally fully populated, a high excitation power is needed to produce a population inversion relative to the ground level – over 50% of the Cr^{3+} ions must be raised to the excited state to achieve laser action. The blue and green wavelengths of a flashlamp are used for excitation. Chromium ions are pumped from the $^4A_2$ ground level into the broad $^4F_2$ and $^4F_1$ bands of the absorption bands. Ions then relax very rapidly through non-radiative transitions to the more sharply defined upper laser levels, by transferring energy to the crystal lattice with the evolution of heat. The upper laser level has a relatively long lifetime, around 3 ms, which enables high amounts of energy to be stored, giving pulses of high peak power. This state then decays to the lower laser level over about 3 ms by emitting red photons of wavelength 694.3 nm.

The optical cavity is constructed from a ruby rod, typically between 3 and 25 mm in diameter with a length up to 20 cm. (Longer rods are difficult to grow, and the internal parts of larger diameter rods are difficult to excite optically.) The cavity is bounded by one totally reflecting mirror and one partially reflecting mirror, which are normally flat, or slightly concave to limit the effects of thermal lensing.

In free-running operation, the ruby laser produces pulses of energy up to about 100 J, with millisecond pulse duration, giving a peak power of about 70 MW, with a repetition rate of one pulse per second. The multimode nature of the output leads to spikes of power, corresponding to emission bursts during excitation, which are superimposed on the pulse envelope. In the oscillator–amplifier configuration, pulse energies greater than 100 J can be obtained with multiple transverse modes. In Q-switched operation, pulses with several joules of energy are possible, with a length on the order of tens of nanoseconds, giving a peak power of about 100 MW and a repetition rate of around 1 Hz. The output can be mode locked using a dye because of the multimode operation, to give pulse trains a few hundred nanoseconds in length containing 20–50 pulses. Individual pulses can be 3 or 4 ps long, with individual pulse energies of approximately 1 mJ in a TEM_{00} beam. Output from a ruby laser is plane polarized if the crystal is cut such that the *c* axis lies perpendicular to the laser axis, but can be randomly polarized if the *c* axis lies parallel to the laser axis. The wall plug efficiency is relatively low, between 0.1 and 1%.

A high pulse energy and spiked output endows the ruby laser with good spot welding and drilling properties. It is not surprising that one of the first industrial applications was piercing of holes in diamonds for wire-drawing dies. However, a compromise between pulse energy and repetition rate is necessary – only one pulse can be generated every second, and so the average power available is limited. Consequently other types of laser, such as the pulsed Nd:YAG, are now favoured in many of the original material processing applications.

Modern ruby lasers are available as stand-alone devices, or packaged systems for specific applications. The beam can be delivered to the workpiece using mirrors, through an articulated arm mirror system, or through a fibre optic. Depending on the application, an end effector is supplied with an adjustable handpiece. This is a particularly important piece of equipment in medical applications – it determines the efficacy of treatment. Packaged systems also include software for control and monitoring.

One of the fastest growing application areas for the ruby laser is cosmetic surgery. Free running devices are used to remove unwanted hair – now a multimillion dollar business in the United States alone. Melanin in the hair absorbs red light, and converts it into heat, which is conducted into the hair follicle, destroying it. The millisecond pulse length matches the thermal relaxation time of the hair. The nanosecond pulse length of Q-switched devices is used in the removal of tattoos and skin blemishes since certain tattoo dyes and melanin strongly absorb red light, in contrast to the surrounding skin. Other applications take advantage of the visible, coherent nature of ruby laser light, and include interferometry, non-destructive testing, holography and plasma measurement. The price of a ruby laser depends on the complexity of the system into which it is built: a sophisticated unit for cosmetic surgery with articulated arm beam delivery can cost about $70 000, whereas a simpler laboratory device designed for spectroscopy typically costs around $10 000. The market for used machines is lively.

Alexandrite

Alexandrite is closely related to ruby, since the active ion is chromium. The host is $BeAl_2O_4$. Alexandrite laser output lies around 800 nm, is tunable, and can be Q-switched. Excitation is normally by arc lamps or flashlamps. Power levels close to 100 W are available. The wavelength is shorter than that of the Nd:YAG laser, giving improved absorption properties with metals. Light of wavelength 755 nm from a flashlamp-pumped long pulse (3 ms) alexandrite laser is an effective means of removing hair follicles and skin pigmentations.

Ti:sapphire

The active medium in the Ti:sapphire laser is a host of sapphire (Al_2O_3), doped with small amounts (less than 0.0015% by weight) of titanium ions (Ti^{3+}). The sapphire host is robust; it has a high thermal conductivity, and is mechanically rigid and chemically inert. The laser transition takes place between the $E_{3/2}$ excited state and the $^2T_2$ ground state. The resonator can be configured in several amplifier stages to achieve high power levels.

The optical cavity comprises a Ti:sapphire rod, typically about 20 mm in length, optical elements to produce a short pulse length, and two focusing mirrors. Energy is absorbed over wavelengths between 450 and 600 nm, and so a wide range of pump wavelengths is possible. However, the short lifetime in the upper laser level (3.2 μs) leads to a high pump threshold, making flashlamp pumping difficult. A frequency-doubled Nd:YAG laser or a continuous wave argon laser (c. 500 nm wavelength) is therefore used for excitation.

Ti:sapphire output has a broad bandwidth, which allows it to be tuned between 680 and 1100 nm. Mode locking and chirped pulse amplification (CPA) are used to compress pulse lengths to the femtosecond (10^{-15} s) level.

Commercial machines for materials processing are available with a wavelength around 800 nm. The output of the Ti:sapphire laser is characteristic: a short pulse length (on the order of femtoseconds); a high pulse energy (on the order mJ); a high repetition rate (a few kHz); and a high beam quality ($M^2 = 1.5$), which is close to TEM_{00}. The Ti:sapphire laser lies at the heart of photoablative microstructuring systems. Electronic components are trimmed and layers selectively ablated with an accuracy on the order of 1 μm. Applications are found in medicine, electronics, and optoelectronics. The laser can be tuned to different wavelengths to treat different types of pigmented lesions on the skin. It is also used in photorefractive keratectomy (PRK) and lithotripsy, where the beam is guided to the kidney via an optical fibre. The output is also suitable for selectively removing coatings or deposits from buildings and sculptures.

Diode-pumped Solid State

Diode-pumped solid state (DPSS) lasers take advantage of the ability of diode lasers to optically excite active media in the form of insulating solids in a variety of geometries. In addition to YAG and glass, host materials used in DPSS lasers include yttrium lithium fluoride ($YLiF_4$, known as YLF) and perovskite ($YAlO_3$, YAP). Neodymium and other lanthanides such as holmium (Ho), erbium (Er) and thulium (Tm) are used as dopants.

DPSS lasers are efficient, reliable, long-lasting sources able to produce a multikilowatt beam with a quality that is superior to conventional lamp-pumped units. When combined with non-linear frequency conversion, these lasers can produce output that spans the spectrum from the ultraviolet to the mid-infrared. Operation can also range from subpicosecond pulses to continuous. They are small, which facilitates incorporation into moving laser processing systems. The wall plug efficiency can be up to three times that of lamp-pumped lasers, with maintenance intervals about 20 times longer. These factors provide DPSS lasers with a competitive advantage in applications such as material processing, medicine, metrology and remote sensing.

The diode laser pumps can be placed in a variety of orientations, which enables active media to be made in novel geometrical shapes, such as slabs, discs, fibres and tubes, discussed below. High pumping intensities are possible because the thermal gradients induced can be aligned with the direction of beam propagation. Efficient cooling can be achieved by placing heat sinks on appropriate faces of the active medium.

The active medium in a *slab laser* is a rectangular-shaped crystal, which is excited and cooled through its longitudinal faces. The beam is internally reflected at the slab walls, taking a zig-zag path through the active medium. In comparison with other geometries, a relatively large volume of active medium can be excited. Improved cooling reduces thermal lensing, enabling greater power and a higher quality rectangular beam to be extracted. (M^2 values between 2 and 3 may be obtained from slab lasers.) The optical quality of the crystal is less critical than the rod design because beam irregularities are smoothed in the extended optical path. However, crystals in the form of slabs are more expensive than rods. Both flashlamp-pumped and diode-pumped slab designs have been constructed.

The geometry of the active medium in a *disc laser* is similar to that of a coin, with an aspect ratio (diameter:thickness) around 20. The aspect ratio is determined by the requirement for sufficient light amplification along the disc axis and adequate cooling through the face(s). One face of the disc is coated to create the optical cavity. High intensity excitation is possible because the thermal gradients induced are aligned with the axis of the disc. (The thermal lens of a disc scales inversely with its thickness.) Efficient cooling is achieved by placing a heat sink on one of the disc faces. The beam quality is high because the principal thermal gradients lie along one dimension. Output power can be scaled to multikilowatt levels without degrading beam quality – a notable advantage of this cavity design, and the reason for the interest in its use in production line welding and cutting operations.

The cavity of *tube lasers* is made by boring a cylinder from a rod and placing the flashlamp inside or outside the tube. The absorption of pumping energy is high and thermal lensing is low, such that a high power beam of high quality can be produced.

Active media can also be made in the form of *fibres*. The fibre is bounded by an end mirror and an output coupler. Fibre lasers may be pumped at their ends or along their length. The intensity of end pumping can be increased by cladding the fibre in a material of different refractive index: energy incident on the larger clad cross-section is internally reflected in the cladding (in a similar manner to a fibre optic), effectively pumping the fibre along its surface. By arranging fibres in modules, output power can be scaled while beam quality, which is determined by the dimensions and numerical aperture of the cavity, is maintained. Compact lasers can thus be produced without the need for a chiller, or output power can be scaled to multikilowatt levels with suitable cooling. The beam is of high quality (close to diffraction-limited) and has low divergence, because the ratio of the fibre diameter to its length is small.

Nd:YAG

Conventional Nd:YAG rods can be pumped using diodes (in addition to the lamps described earlier), which may be located at the ends of the rod or along its length. The former is more common in low power machines, in which a high quality beam mode can be generated. The gallium aluminium arsenide (GaAlAs) diode laser emits light of wavelength 807 nm, which corresponds with an absorption band of neodymium ions. The excitation efficiency is therefore high (30–40%). In comparison with lamp pumping, the low thermal load on the rod results in an improved beam quality, higher pulse rates, superior pulse repeatability and longer lifetimes.

The higher beam quality of diode-pumped Nd:YAG lasers provides a number of advantages for material processing: the smaller focused diameter gives higher power density; resonators and optics can be more compact, and larger working distances can be used. Diode-pumped Nd:YAG lasers are available with multikilowatt power levels for a variety of material processing applications. Frequency-doubled output challenges the conventional argon ion gas laser in the important blue–green portion of the spectrum for reprographics.

Er:YAG

The Erbium:YAG laser is ideal for cosmetic procedures on delicate skin, such as the hands and neck, and fine lines and wrinkles on the face and around eyes. This laser is also used to prepare dental cavities. Output from the Er:YAG laser can be frequency quadrupled to give pulsed blue–indigo light.

Er:YLF

Erbium can be doped to levels around 8% in a YLF host. Efficient diode pumping is achieved with a wavelength of 797 nm. The laser transition in the Er:YLF laser takes place between the $^4I_{11/2}$ (upper level) and $^4I_{13/2}$ (lower level), which results in the emission of a photon of wavelength 2800 nm. This wavelength lies close to the absorption peak of water molecules, and so the laser finds many applications in medicine.

Ho:YAG and Ho:YLF

Pulsed light from the Ho:YAG and Ho:YLF lasers is effective in lithotripsy as a means of removing urinary calculi (e.g. gallstones) by photochemical decomposition.

Yb:YAG

In comparison with the Nd:YAG crystal, the maximum doping level of Yb in YAG is higher (25% versus 1.5%), the absorption bandwidth is larger (reducing thermal loading), and the upper level lifetime is longer (enabling more energy to be stored). Yb:YAG has a maximum absorption efficiency near 940 nm, and so it can be pumped efficiently by InGaAs diodes, which are more robust than the AlGaAs diodes used to pump neodymium lasers. (When flashlamp pumping was the only means of excitation, the Nd:YAG laser had a competitive advantage.) Output is generated in wide emission bands, suitable for ultrashort pulse operation. Frequency doubling results in an output wavelength of 515 nm, providing the potential to replace the larger volume Ar ion laser, which emits a wavelength of 514 nm.

Superkilowatt output of high beam quality can be obtained from a Yb:YAG disc several millimetres in diameter with a thickness less than 1 mm because of efficient excitation and cooling. Multikilowatt output is available from modules of Yb-doped fibres. The cost of such kilowatt-class lasers lies around that of comparable lamp-pumped YAG lasers, but less floor space is required, and maintenance intervals are longer. They are particularly suitable for cutting and welding.

Nd:YLF

YLF is the most common alternative to YAG as a host for neodymium doping: it has a lower thermal conductivity and is not as hard, but exhibits less thermal lensing and can operate continuously at room temperature.

Nd:YAP

The crystal anisotropy of YAP results in a small tuning range of wavelength. Nd:YAP lasers are used in dental procedures.

Nd:GGG

A laser made with gadolinium gallium garnet ($Gd_3Ga_5O_{12}$, GGG) doped with neodymium produces light of wavelength 1061 nm. GGG crystals can be grown more easily than YAG crystals, and so the possibilities of producing sources of high average power are greater. Such units are of interest in inertial confinement fusion (Chapter 17) and military laser systems.

Tm:YAG

Thulium-doped YAG solid state lasers that operate at 2 μm wavelength have many applications in medical, remote sensing and military technologies.

Colour Centre

Colour centres (or F-centres) are formed when molecules or ions are bound to neighbouring vacancies. Lithium fluoride doped with [illegible] and magnesium has been used to host molecular fluorine and F_3^+, which contain two electrons bound to two and three neighbouring anion vacancies, respectively. The colour centre is produced by irradiation with a femtosecond pulse. Visible light in the red–green range can be produced. Such lasers are suitable for the construction of miniature optical devices.

Semiconductors

Before describing the workings of a semiconductor laser, it is worthwhile considering the terminology used today. The terms *semiconductor laser* and *diode laser* are often (correctly) used interchangeably. However, the term *laser diode* sometimes appears (incorrectly) in the same context. A laser diode refers to the combination of the active medium, photodiode chip used to control the power, and housing, which are combined with electronics and optics. Note also that a *light emitting diode* (LED) can be thought of as a laser diode without an optical cavity for feedback. The term *semiconductor laser* is used here when describing the physics of operation, and *diode laser* used when referring to commercially available units.

A semiconductor laser is an edge emitting device with a Fabry–Perot optical cavity, illustrated in Fig. 5.22a. The front and rear facets of the cavity are normally coated to act as mirrors, and the sides are roughened to reduce reflection back into the laser. (The beam may also be extracted from the top surface by creating an appropriate cavity.) Excitation is by electrical means, which results in direct injection of electrons into the active medium. Small (100 μm long) emitters are arranged in a bar about 1 cm in length. Many tens of watts of power can be extracted from a single bar. Laser output therefore comprises beams from a large number of individual sources, which creates a high beam divergence (because of diffraction effects) and a relatively poor beam quality in comparison with solid state laser output. The raw beam is suitable for surface treatment, but must be manipulated for penetration processing. A variety of cooling geometries have been designed, including backplane cooling of many laser diode bars by a single heat sink, or the use of individual heat sinks attached to each diode bar. Output may be delivered directly to the workpiece, or via a fibre optic.

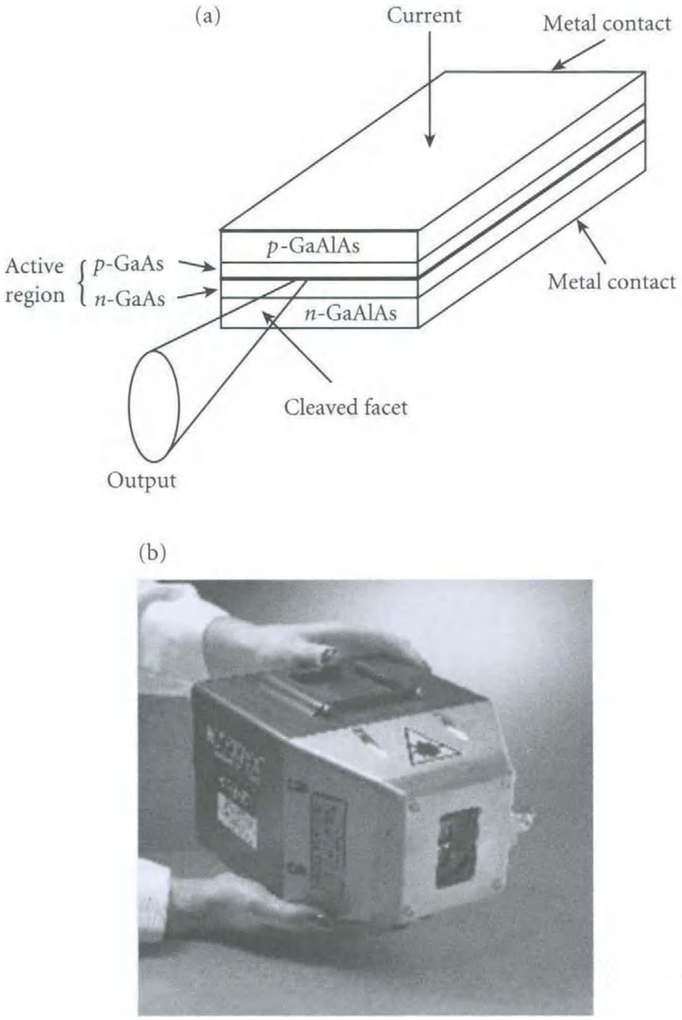

Figure 3.22 Diode laser: (a) schematic illustration of a Fabry–Perot double heterojunction semiconductor structure; (b) Nuvonyx ISL-4000L 4 kW InGaAlAs diode laser head. (Source: Tom Pallett, Nuvonyx Inc., Bridgeton, MO, USA)

Diode lasers originally found use in low power communications devices. In 1991, commercial diode lasers cost around $2000 per watt. By 1999 the price had fallen to $100 per watt, because of growing markets and investment by laser manufacturers. Diode lasers are consequently replacing other light sources for many medical, graphical and illumination applications.

Diode laser heads are now packaged with beam manipulation optics to give multikilowatt output for material processing – one is shown in Fig. 3.22b. The relatively short wavelength, scale of power output, and rapid control over power modulation provide benefits for processing materials. Performance is better than that obtained from an Nd:YAG laser of comparable power, provided that there are no particular absorption problems at the wavelength used. The laser head is sufficiently compact to be mounted directly on an articulated robot. Key benefits for users include compactness, high efficiency, high reliability, and low maintenance. Because diode lasers have high electrical-to-optical power conversion efficiency (up to 50%), they can deliver light for myriad applications based on heating or illumination at a fraction of the power consumption, cost and bulk of competing laser and non-laser sources. The nature of the application determines the most suitable wavelength and power, and hence the type of diode laser used.

GaAs

The principle of light generation in semiconductors was first demonstrated in gallium arsenide (GaAs). Early diode lasers took the form of a *p*–*n* junction comprising an *n*-type GaAs host into which atoms such as zinc were diffused to create a heavily doped *p* region. Low power, divergent, multimode, infrared light is produced from the homojunction GaAs laser. Only pulsed output can be obtained because CW operation results in overheating and damage, without active cooling. Heterojunction lasers, which comprise layers of different semiconductors, are therefore now used for material processing.

InGaAs

By doping with indium (In), a heterojunction laser capable of higher power output than the GaAs device can be constructed, shown schematically in Fig. 5.23a. The preferred wavelength for material processing is 940 nm.

InGaAlAs

Very stable output in CW or pulsed mode can be achieved from InGaAlAs diode lasers. CW output in the range 750–850 nm can be produced from a single unit. Multikilowatt power levels can be extracted from diode laser arrays. Output of wavelength 808 nm is favoured for material processing. The beam is normally elliptical, with quality values (M^2) of 1.02 and 1.3–100 parallel and perpendicular to the junction, respectively, depending on the injection current.

GaN

The gallium nitride (GaN) laser was developed in 1995 for use in optical memory devices. Output lies in the blue–violet.

Lead Salt

The infrared output from the lead-salt laser can be tuned by adjusting the laser's temperature or the excitation current. These lasers are normally cryogenically cooled, but recent developments have removed the cooling requirements, which will lead to new applications in industry, research and process control. Such lasers are used for trace measurement of pollutants in the atmosphere and the analysis of reaction kinetics.

SUMMARY AND CONCLUSIONS

Laser light has unique properties: coherence (spatial and temporal), monochromaticity, low divergence and high brightness. Lasers can be categorized according to the nature of the active medium (gas, solid or liquid). Gas media comprise molecules, atoms, ions and excimers. The principal liquid media are organic dyes. Solid media include insulating crystals and semiconductors. Laser light interacts with materials through thermal, photochemical, photoelectric and photophysical modes.

Designs for gas lasers are becoming more compact to reduce the floor space required, and more efficient in their use of gases, which reduces running costs, while output power is continually rising. The popularity of the carbon dioxide laser can be attributed to a number of favourable properties. Pulsed or continuous wave emission is produced in a high quality beam at multikilowatt power levels. Far infrared light is transmitted easily in air, and is absorbed by a wide range of engineering materials. Designs, which are relatively simple and robust, are scaled easily to high power levels. The capital cost is relatively low (around $100 per watt). The wall plug efficiency is high (up to almost 20%), and consumable costs are low, leading to a relatively low cost of ownership.

Growth in the use of diode-pumped solid state lasers (DPSS) is expected to be vigorous because of the design opportunities that this form of excitation affords. Novel geometries of active media can be produced, with the design optimized for particular properties such as output power, or beam quality. Multikilowatt DPSS lasers compete with gas and lamp-pumped solid state devices; the benefits that they offer (compactness, high power efficiency and high beam quality) will mean that they are likely to replace many of the traditional large-scale material processing sources.

The luminous performance of visible light emitting diodes (LEDs) has increased by a factor of 10 every decade since the 1960s (Craford's law). The cost of diode lasers fell by a factor of 10 during the last decade of the twentieth century. Diode lasers, now available in multikilowatt designs, are suitable for direct material processing. Their application can be expected to grow at a similar rate to LEDs (which are now rapidly replacing incandescent sources of light).

Ultrashort (femtosecond scale) pulsed sources and high energy ultraviolet excimer lasers have improved the accuracy of athermal micromachining by several orders of magnitude. Lasers that once were thought to have insufficient power for material processing are increasingly finding uses in small-scale machining such as lithography. As photonics takes over from electronics, the use of such laser-based microfabrication techniques will increase.

Efforts continue to extend the wavelength range of lasers. The output from free electron sources, dyes, and certain solids can be tuned to given wavelengths. High energy short wavelength output is available from X-ray lasers.

When sources become sufficiently compact, and are packaged into dedicated turnkey systems, their field of application grows rapidly. For example, as soon as laser-based surgical and cosmetic procedures could be performed by practitioners using commercial turnkey systems, exponential growth was experienced worldwide. Such 'packaging' of lasers in material processing systems is the subject of the next chapter.

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