Chapter 4 | Trends in Laser Development

Chapter 3 discussed details of many of the practical types of lasers that are now available. The emphasis was on commercially available devices, rather than on experimental models. The chapter presented tabulations of the characteristics of commercial devices. In this chapter, we discuss prospects for future developments.

We begin by discussing conventional lasers, that is, types that are well developed and widely available. These include gas lasers such as helium–neon, argon, CO_2, solid state lasers like Nd:YAG, and semiconductor lasers. These lasers have been available for many years and have reached some level of maturity. For some of these types, the most important developments in recent years have involved reliability and improved lifetime, with modest increases in output power. Early in the history of lasers, a laser was a fragile device, requiring considerable care and maintenance. That situation has changed. Lasers have become durable, reliable, and reasonably economical to operate. One outstanding example is the semiconductor laser. Early models were very short-lived (hours). Advances in structures and fabrication have made them very long-lived (years) if they are treated properly.

Some types of lasers have not advanced substantially in recent years, and prospects for rapid future change do not appear likely. These include some of the gas lasers like helium–neon and argon, and some lamp-pumped solid state lasers like Nd:glass and ruby. These relatively mature lasers appear to have reached a plateau in their development. In some cases, they are being replaced by other laser types for established applications.

We note that there have been advances in some lamp-pumped lasers, like the vibronic solid state lasers discussed in Chapter 3. These advances seem likely to continue.

Two types of established lasers are rapidly advancing, with considerable research and development effort devoted to them. These are semiconductor lasers and diode-pumped solid state lasers. We may expect substantial advances in these two classes, which we will describe in some detail.

We also describe classes of lasers that have been developed for some time, but that have not reached a status of wide commercial availability. These are chemical lasers, free electron lasers, and x-ray lasers. We will describe a tunable device, the optical parametric oscillator, which is becoming commercially available. We will conclude the chapter with a discussion of the availability of tunable laser technology.

A. Semiconductor Lasers

Semiconductor lasers are the subject of extensive research and development worldwide. It is not possible to summarize all research efforts in semiconductor laser technology here; we do note that the worldwide efforts should improve the performance parameters of commercially available devices in the near future. There are many experimental efforts that have the goals of increasing available power, especially in the visible spectrum, of extending device lifetime, of improving beam quality, of providing blue and ultraviolet semiconductor lasers, and of improving characteristics for semiconductor lasers operating in the red portion of the visible spectrum.

There is extensive development in the area of vertical cavity surface emitting lasers (VCSELs), which were described briefly in Chapter 3. VCSELs offer the advantage of easy packaging in two-dimensional arrays on a chip. Many different approaches to fabrication of VCSELs are being investigated. VCSELs are beginning to be commercially available. It appears that more types of VCSELs should become available, and that use of VCSELs in selected applications should become common.

Other research areas with high interest include development of advanced quantum well structures, development of semiconductor lasers with a master oscillator, power amplifier structure in order to increase output power without damage, and continued development of multielement array structures, especially structures in which the light from the individual structures is coupled to form beams with narrow spectral linewidth and high beam quality.

Quantum well structures, in particular, mentioned in Chapter 3, represent an important advance. In a quantum well laser, one or more very thin layers of a semiconductor are sandwiched between layers of a semiconductor with wider bandgap. The layer thickness is of the order of 10 nm or less. The structure can be a single quantum well, with one layer of the narrow-bandgap material, or a multiple quantum well, with many layers. A multiple quantum well structure is sometimes referred to as a superlattice. Quantum well devices using materials in the AlGaAs system are becoming common. As the dimension of the layer approaches the wavelength of the charge carriers in the material, the properties of the material change. The properties of quantum well materials are different from those of bulk semiconductors of the same composition. The properties are affected by the confinement of carriers in the potential well defined by the larger-bandgap layers. Confinement of charge carriers in the quantum well increases the gain coefficient and reduces the threshold current for laser devices. The width of the quantum well provides tuning for the laser, because the effective bandgap of the material changes. Lasers based on quantum well structures have become commercially available, and their use should continue to increase in the future.

There is extensive effort devoted to development of semiconductor lasers operating in the blue and ultraviolet portions of the spectrum. In the blue portion of the spectrum, low-power laser sources have been limited to helium–cadmium lasers and air-cooled argon lasers. Both these sources are inefficient and costly, consume relatively large amounts of power, and are larger than desirable. The availability of an efficient compact semiconductor laser source in this region would open up new applications.

In particular, blue semiconductor lasers would be of great interest for optical disk recording. The areal density of information that can be stored on an optical disk is inversely proportional to the square of the wavelength used. Most optical storage devices have used aluminum gallium arsenide lasers operating at wavelengths near 780 nm. If one had a blue semiconductor laser available, the density of information stored could be increased nearly fourfold. Considerations such as these are driving the development of short-wavelength semiconductor lasers.

One approach has been direct frequency doubling of diode laser output. In one system that has become commercially available, an 860 nm, continuous, single-mode laser diode is doubled to produce a 430 nm output. The doubling is performed by a nonlinear optical crystal in an external resonant cavity. The frequency of the input signal is locked to a mode of the cavity. The output is a TEM_{00} beam with power greater than 10 mW.

Another approach has been to use diodes of II–VI compounds to generate short-wavelength laser light directly. Devices based on materials such as zinc sulfide selenide or cadmium zinc selenide have been fabricated as double heterostructures and operated as lasers. Continuous room temperature operation at a wavelength around 490–510 nm has been achieved in laboratory devices, at power levels up to 10 mW. These blue-green semiconductor lasers are not yet commercially available in the mid 1990s, but they will likely become available soon.

Another recent development is the operation of laser diodes based on gallium nitride (GaN) [1]. The first GaN lasers operated at 417 nm, in the violet, and additional wavelengths of operation at 402 and 376 nm have been announced. This extends the range of operation into the ultraviolet. GaN offers excellent material properties for reliable, long-lived devices. It will undoubtedly become an important short-wavelength semiconductor laser material.

At the red end of the visible spectrum, $Al_xGa_yIn_{1-x-y}P$ semiconductor lasers continue to advance. The power levels available continue to increase, and the shorter wavelength models keep appearing. These lasers are replacing helium–neon lasers in some applications.

The price of semiconductor diode laser arrays should continue to decrease. This will allow their use in a wider variety of applications.

B. Diode-Pumped Solid State Lasers

Lamp-pumped solid state lasers were developed early in the history of lasers and after some time reached a level of maturity. For a number of years, the technology of solid state lasers did not advance much. But in recent years, solid state lasers have seen rapid development and change. This is mostly due to the development of semiconductor diode-pumped solid state lasers. Diode-pumped devices offer the capability for much higher efficiency and smaller size than lamp-pumped lasers of similar output. The efficiency in turn reduces the amount of waste heat that must be removed, so that the accessory equipment, like the chillers, also are much more compact. Commercial models of diode-pumped solid state lasers have been available for a number of years, and their output power has been increasing steadily.

Another important area involves advances in solid state laser technology at shorter wavelengths, especially in the green portion of the spectrum. For many years, the argon laser has been the dominant laser source in the green. But argon lasers are inefficient, large, and expensive. Advances in frequency-doubled diode-pumped Nd:YAG lasers provide a compact, efficient, and more economical source of green laser light. The availability of green diode-pumped solid state lasers should allow development of applications in areas such as display, medicine, and remote sensing, that are difficult now.

We may expect to see diode-pumped frequency-doubled Nd:YAG lasers replacing argon lasers in areas where electrical power, size, and cooling are important issues. It is also likely that green diode-pumped solid state lasers will replace argon lasers for pumping Ti:sapphire lasers and will replace lamp-pumped Nd:YAG lasers for some micromachining applications. The extent to which green solid state lasers will replace other lasers in established applications will depend on how rapidly the price of diode lasers decreases.

The applications of green Nd:YAG lasers have been limited in some cases by what has been called "the green problem." The output of continuous frequency-doubled solid state lasers is subject to random fluctuations in output power, as we now describe.

Because the efficiency of frequency doubling increases with the optical power, doubling is usually performed with the doubling crystal in a resonant optical cavity to increase the power level. Frequency doubling may be performed with the doubling crystal within the original laser cavity (intracavity doubling) or with the crystal in an external resonant cavity, outside the cavity of the fundamental laser. In the intracavity case, the presence of high-intensity light confined within the laser cavity leads to efficient doubling. But often, more than one longitudinal mode will be present. The green problem arises when several longitudinal modes couple via the nonlinear interactions. As a result of these interactions, a strong amplitude modulation is imposed on the green output.

Research workers have devoted substantial efforts to the solution of this problem. The green problem may be solved in intracavity doubling if the laser is constrained to operate in a single longitudinal mode. The use of an external resonant cavity allows enhancement of the optical field at the position of the doubling crystal, leading to efficient doubling. It also allows separate optimization of the original laser cavity and the cavity in which doubling is done. Models of stable green Nd:YAG lasers have been developed using both intracavity doubling and external cavity doubling.

Although progress has been made, highly stable continuous green Nd:YAG lasers are still not available at output powers of more than a few hundred milliwatts, although laboratory devices emitting more than 5 W have been demonstrated. But the conditions for stable operation are sensitive. Small fluctuations can destabilize the output. Extremely precise thermal control is required to stabilize such lasers. Thus, advances in the development of stable high-power continuous green solid state lasers are likely to be slow.

The situation is different with pulsed green lasers. The *Q*-switched operation of green solid state lasers becomes simpler. *Q*-switched green solid state diode-pumped lasers are available with average power outputs at the multiwatt level. Potential applications for these devices include laser radar, micromachining, and environmental monitoring.

In addition, diode-pumped solid state lasers are moving into the ultraviolet. Laboratory demonstrations have yielded more than 1 W of continuous output from a frequency-quadrupled Nd:YAG laser at 266 nm. Although such lasers are not on the market yet, it seems likely that they will be in the near future. Such devices could have applications to microelectronic fabrication, optical disks, and medicine. *Q*-switched frequency-quadrupled Nd:YAG lasers operating at 266 nm are available with average power near 1 W.

Another research trend involves the development of microchip laser devices. Diode-pumped microchip lasers are very small, efficient, and easy to fabricate. An example of a possible structure for a diode-pumped *Q*-switched Nd:YAG microchip laser is shown in Figure 4-1. The Nd:YAG is in the form of a small slab with millimeter or submillimeter dimensions. It is pumped by a diode laser. The lithium niobate *Q*-switch is also in the form of a small chip, bonded in close proximity to the Nd:YAG. The left mirror is high reflectance at 1060 nm and low reflectance at 810 nm. The center and right mirrors are partially transmitting at 1060 nm. This configuration uses flat mirrors and is very simple to fabricate. In practice, some microchip lasers have used one curved mirror to stabilize the cavity. The design

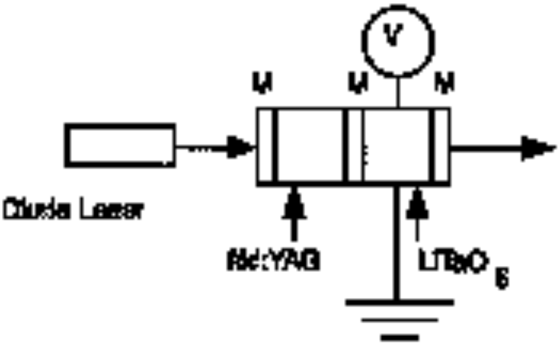

Figure 4-1 A diode-pumped, *Q*-switched Nd:YAG microchip laser. The mirrors are denoted *M*. The source of voltage for the *Q*-switch is denoted *V*.

shown in the figure could be considered typical, but there have been many variations, including frequency-doubled devices operating in the green.

Because the laser cavity is very short, there will be only one longitudinal mode within the gain curve of the material. This means that the microchip lasers are stable, single-mode devices.

The fabrication of microchip lasers is very simple, and well suited to mass production. Because of the easy fabrication and the small amount of material required, the cost can be low. Availability of microchip lasers as inexpensive, very small, stable, and efficient sources could enable new applications to become practical. Although some miniaturized diode-pumped solid state lasers are being marketed, the full potential of microchip lasers has not yet been realized. They should continue to develop.

Other developments in solid state lasers include new materials and advances in tunable devices. Tunable solid state lasers are replacing dye lasers for some spectroscopic applications.

In the area of new materials, solid state lasers based on materials with vibronic energy levels will continue to advance. Development of Ti:sapphire lasers will continue, especially in the area of very short (femtosecond) devices, useful for basic scientific studies. Lasers based on the materials Cr:LiCAF and Cr:LiSAF have been under development in a number of laboratories and should become commercially available soon. The long-wavelength end of the Cr:LiSAF absorption spectrum overlaps the emission of $Al_xGa_yIn_{1-x-y}P$ semiconductor diodes in the 670 nm region. Diode-pumped Cr:LiSAF lasers have been demonstrated and could form the basis of an all-solid-state laser system, although increases in efficiency and power are required.

Nd:YAG has been the dominant solid state laser material for many years. It probably will be challenged for use in some applications by the development of new solid state laser materials.

C. Chemical Lasers

Chemical lasers employ a chemical reaction to produce a population inversion. They offer the possibility of operation without an electrical input. All the required energy could be produced in the chemical reaction. One simply mixes chemical agents and allows them to react. In practice, most chemical lasers do use an electrical input in addition to the chemical energy released.

One of the leading examples of chemical lasers may be summarized by the following set of reactions:

$$\begin{gathered} F + H_2 \rightarrow HF^* + H \\ H + F_2 \rightarrow HF^* + F \qquad (4.1) \\ HF^* \rightarrow HF + h\nu \end{gathered}$$

In the first reaction, a free fluorine atom is required to initiate the reaction. Often, an electrical discharge is used to dissociate fluorine and produce some free fluorine atoms. The excited HF molecule, denoted HF*, produced in the reaction is in an excited state, which is the upper level for the laser transition. In the second reaction, the free hydrogen atom from the first reaction interacts with fluorine to produce excited HF, leaving a free fluorine atom to continue in a chain of reactions. The third reaction indicates the transition of the HF molecule to its ground state, which is not populated in the chemical reactions. This is accompanied by emission of the energy difference as a photon. The population inversion is produced automatically as the chemicals react and yield excited state molecules as their end product. Some electrical energy may be required for initiation, but once the reaction has begun, it can continue as long as the supply of reactants continues.

Table 4-1 shows some chemical laser systems that have been studied. Of these, the most highly developed are the hydrogen fluoride laser, operating at a variety of wavelengths around 3 μm, and the deuterium fluoride system, operating at a number of wavelengths in the 4 μm region. A few commercial models of these two types are available, with DF lasers capable of emitting up to 100 W in a TEM_{00} mode and HF systems capable of 60 W.

The chemical oxygen–iodine laser (COIL), operating at 1.32 μm, is of particular interest because it is potentially scalable to very high power. No commercial models are available, however.

Chemical lasers have been the subject of considerable research and development over many years. They can be scaled to very high powers, in excess of 100 KW in very large models. They have been of potential interest for military applications. Because their wavelengths are shorter than that of the CO_2 laser and their light is better absorbed by metals, they have been of interest for material processing applications. But the corrosive nature of the chemicals used in them has constituted a problem, and they have never become used widely in industry.

D. Free Electron Lasers

Free electron lasers (FELs) represent a specialized class of device. They have received substantial publicity but probably have limited industrial applications. They

Table 4-1 Chemical Laser Types

Reactants	Laser molecule	Wavelength (μm)	Status
H_2–F_2	HF	2.6–3.6	Limited commercial availability
D_2–F_2	DF	3.6–5.0	Limited commercial availability
H_2–Cl_2	HCl	3.5–4.1	Experimental
CS_2–O_2	CO	4.9–5.7	Experimental
D_2–F_2–CO_2	CO_2	10.6	Experimental
O_2–I_2	I	1.32	Experimental

use no solid, liquid, nor gaseous material as the active medium. Rather, the active medium is a beam of relativistic electrons. These electrons have velocity that approaches the velocity of light. A FEL directly converts the kinetic energy of the electron beam into light. The FEL is a novel type of laser with high tunability and potentially high power and efficiency.

The structure of a FEL includes a series of magnets called wigglers, which present an alternating magnetic field to the electron beam. Figure 4-2 shows a schematic diagram of a typical FEL structure. An electron beam is introduced into the laser cavity by magnets. The electrons radiate laser light by stimulated emission. The light emerges through the output mirror. The wavelength of the FEL is a function of a number of factors, including the velocity of the electron beam, the spacing of the wiggler magnets, and the magnetic field. The wiggler spacing may typically be a few centimeters, and the total device length a few meters. Once the device has been constructed, the wiggler spacing is fixed, but the laser wavelength may be tuned by varying the velocity of the electron beam. Operation of FELs at wavelengths from the ultraviolet to the millimeter wave region has been demonstrated at a number of laboratories throughout the world.

Free electron lasers offer a number of potentially valuable properties, such as an essentially unlimited tuning range and the capability of being scaled to high power output. There is no material medium to be damaged. It is easy to extract heat from the laser, and the laser beam quality can be excellent. There has been high interest in FEL technology. Many laboratories and universities have constructed and operated FELs. Their results have received considerable attention throughout the laser community.

One important limitation for FELs is that they require a high-quality beam of relativistic electrons, with low angular spreading and very little variation in electron velocity. These sources are large and expensive. It requires substantial resources to build and operate an FEL. As an example, in the early 1990s, the so-called

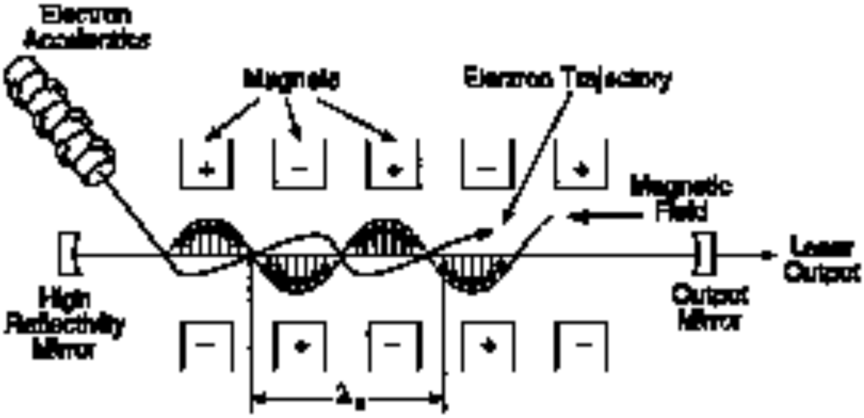

Figure 4-2 Free electron laser

Advanced FEL, developed at Los Alamos National Laboratory, began operation after three years of design and construction [2]. In early operation, the laser operated in the 3–9 μm region, but it should be capable of operating in the visible and ultraviolet also.

This example indicates that FEL development is a major project. Thus, FEL technology will probably not come to widespread use in industrial applications. Potential uses for FELs include military applications, basic research at national laboratories, and possibly medical applications. Large electron beam capabilities exist in the nuclear medicine facilities at large medical complexes, and so these facilities could support the requirements of an FEL.

E. X-Ray Lasers

The desirability of lasers operating in the x-ray region of the spectrum has been known for many years. Many applications would be made possible by the availability of a coherent source of x-radiation. Relatively early in the history of lasers, there were some claims that x-ray laser sources had been developed. These claims are now believed to be spurious.

One problem is the lack of mirrors to form a resonant cavity for x-ray lasers. To date, x-ray lasers been superradiant devices, with only a single one-way passage of light through the material.

One active medium suggested for such lasers was the plasma produced by the interaction of high-power lasers with surfaces. Such plasmas are highly ionized and emit intense x-radiation. It was believed that a population inversion could be produced in some of the high-lying energy levels of multiply ionized species in the plasma.

In the mid-1980s, workers at Lawrence Livermore National Laboratory, using the very large Nd:glass lasers developed for laser-assisted thermonuclear fusion, detected stimulated emission in the 20 nm region when the laser was focused to a line on a thin selenium foil [3]. The emission came from 24 times ionized selenium (Se^{24+}) in the resulting plasma. The experiment involved amplified stimulated emission in a single pass through the plasma, because no mirrors were used. The most convincing evidence that this was laser emission was the fact that the intensity increased exponentially with the length of the plasma.

Since then, a number of different groups have demonstrated x-ray laser operation in highly ionized plasmas produced by very large lasers. The plasmas have involved multiply ionized elements such as germanium, tungsten, gold, yttrium, molybdenum, copper, and tin. The targets have most often been in the form of thin foils, which generate a linear plasma when heated explosively by the laser. The wavelengths have covered a range from 4 to 30 nm. Because the lasers were large and expensive, these demonstrations have not been compatible with practical applications.

In recent work [4], there has been a demonstration of x-ray laser operation in a C^{5+} plasma at 3.37 nm. The plasma was generated by a Nd:glass laser of tabletop size. This result is significant because the size of the laser is more modest than in earlier experiments. It leads toward the possibility of x-ray lasers that do not require prohibitively large laser drivers. It is also important because the wavelength lies in the so-called "water window." This window (2.3–4.4 nm) lies between absorption edges of oxygen and carbon. It is potentially useful for biological studies. One could perform x-ray microscopy on living cells. This work could lead toward practical applications for x-ray lasers.

It is too early to predict what forms x-ray lasers will ultimately take and how extensive their applications may be. The earliest uses will be in the area of basic scientific research, rather than industrial applications. Applications that have been suggested include imaging of living cells, projection lithography with extremely small feature size, and x-ray holography.

F. Optical Parametric Oscillators

Optical parametric oscillators (OPOs) represent another tunable solid state source. These devices are based on nonlinear optical effects. We will discuss nonlinear optics more in Chapter 5, but to make this discussion self-contained, we will summarize some key points here.

In a noncentrosymmetric crystal illuminated by a laser beam, a large dielectric polarization, proportional to the square of the electric field of the laser, can be induced. The nonlinear polarization can radiate energy, permitting harmonic generation at multiples of the incident laser frequency. This is the basis of frequency doubling, tripling, and so on. If two laser beams are mixed in the crystal, radiation at the sum or difference in frequencies of the two beams may occur. In order for substantial buildup of the radiated energy at the new frequencies, a "phase matching" relationship must be satisfied. The wave vectors of the applied fields and the generated field must have the same relation as their frequencies. For sum-frequency generation, if the angular frequencies and wave vectors of the ith wave are ω_i and $\mathbf{k}_i$, respectively, and the subscripts 1, 2, and 3 refer to the first and second incident waves and the output, respectively, then

$$\omega_1 + \omega_2 = \omega_3 \qquad \text{and} \qquad \mathbf{k}_1 + \mathbf{k}_2 = \mathbf{k}_3 \tag{4.2}$$

To satisfy both conditions simultaneously, one selects the crystal orientation, the direction of propagation, and the crystal temperature so that the birefringence of the crystal offsets the effects of dispersion.

The OPO uses nonlinear optical effects to generate two different frequencies, starting with one laser frequency. It is similar to difference-frequency generation. Strictly, an OPO is not a laser, but it generates a coherent optical beam like a laser, and it utilizes a resonant cavity like a laser. But there is no stimulated emission, so it is not a true laser.

In an OPO, a pump beam at frequency ω_p is passed through a suitable nonlinear crystal. Nonlinear interactions in the crystal transfer energy from the pump beam to a signal beam at frequency ω_s and at the same time generate an idler beam at frequency $\omega_i = \omega_p - \omega_s$. The wavelength of operation may be varied by changing the temperature or the angular orientation of the crystal. A simplified configuration for an OPO is shown in Figure 4-3.

In this configuration, the output contains both the signal and idler. The left mirror is transmissive at the pump wavelength, and reflective at the signal and idler wavelengths. The right mirror is transmissive at the pump wavelength, and partially reflecting at the signal and idler wavelengths.

The device may be tuned by changing the phase matching conditions. The indices of refraction of the crystal at the three relevant wavelengths in the directions of beam propagation may be varied by changing the temperature of the crystal or by rotating the crystal. As a result, one obtains two beams with variable wavelength, the signal beam and the idler beam.

OPOs have been under development for many years and have become commercially available in the early 1990s. There has been substantial recent research interest in OPOs. Laboratory devices have demonstrated tuning from the ultraviolet to 14 μm in the the infrared. Other developments have included the first continuous devices and lower-cost technology.

Commercial devices tend to have short pulse durations (as short as femtoseconds) and are tunable in different ranges in the visible and near infrared. One device, for example, offers tuning of the signal from 410 to 690 nm and the idler from 730 to 2000 nm. If frequency doubling is used, the tuning range can be even wider.

OPOs represent a tunable all-solid-state device. Models available cover a broad wavelength range in the visible and infrared portions of the spectrum.

G. Tunable Lasers

In Chapter 3 and in the foregoing discussion, we have mentioned a number of tunable lasers. Because tunability is an important feature for many spectroscopic and photochemical applications, we summarize the availability of some leading tunable lasers in this section. It is beyond the scope of this chapter to enumerate them all.

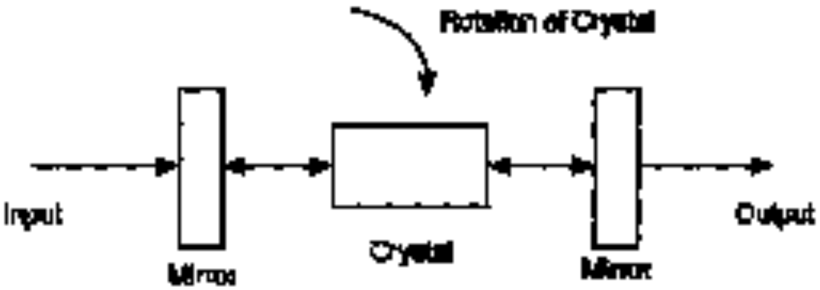

Figure 4-3 An optical parametric oscillator.

The use of nonlinear optical effects can increase the range of tunability for a tunable laser. For example, if one frequency doubles a laser tunable from frequency ω_1 to ω_2, the output is tunable from $2\omega_1$ to $2\omega_2$. If one mixes the output from a tunable laser in a nonlinear crystal with a fixed laser frequency, sum-frequency generation will yield a tunable output at a higher frequency and difference-frequency generation can yield an output at a lower frequency. Thus, use of nonlinear optical effects can greatly increase the spectral range of tunable lasers.

The leading tunable laser in the near ultraviolet, visible, and near infrared regions has been the dye laser, offering reasonably high power, narrow linewidth, and a broad tuning range. It has been employed for many studies of molecular structure and chemical reactions.

Tunable solid state lasers, such as Ti:sapphire, which offer a broad tuning range without the need to change dye materials, have begun to compete strongly in the visible and near infrared regions and have displaced dye lasers for some applications. With frequency doubling, they cover most of the range from 0.35 to 1.1 μm.

In the near infrared, $Al_xGa_{1-x}As$ and $In_xGa_{1-x}As_yP_{1-y}$ lasers and, in the long-wavelength infrared, lead compound semiconductor lasers are tunable by means of varying temperature and operating current. Many excellent spectroscopic studies have been performed with them. Any one device has a relatively limited tuning range. Thus, they are best suited for very high resolution spectroscopy within a narrow spectral range. In addition, mode hopping can make it difficult to reach any specified wavelength. Thus, it is desirable to use a semiconductor laser that does not exhibit mode hopping.

Raman shifting is a means that may be employed to extend the range over which a tunable laser may be tuned and to provide specific desired wavelengths that the laser could otherwise not reach. Raman scattering involves transfer of some of the energy of a photon to internal modes of a molecule. The frequency of the scattered light is shifted by a specific amount, characteristic of the molecular species. As a result, the range of available wavelengths may be expanded. Raman shifting has been used most often in experimental equipment, but some models are commercially available. The operation of Raman shifters will be described in the next chapter.

Optical parametric oscillators (OPOs) represent another tunable solid state source, based on nonlinear optical effects. They have been under development for a long time and are now becoming more widely available. They may be tuned by temperature or by rotating a crystal. Models available cover a broad wavelength range in the visible and infrared portions of the spectrum. Different commercial models cover at least the range from the blue portion of the visible spectrum to the mid infrared, near 4 μm. The short-wavelength end of the range can be extended by frequency doubling. For a single device, the tuning range can be relatively long. One commercial device, for example, covers the range from 1.45 to 4 μm. Most commercial models are short-pulse devices.

Finally, the free electron laser (FEL) offers potentially the ultimate in tunability, in principle being unlimited in its tuning range. Models of FEL devices have operated at wavelengths ranging from the ultraviolet to the millimeter wave region. As

Table 4-2 Tunable Lasers

Type	Tuning range	Comments
Dye	UV to near IR	Needs another laser as pump; range includes frequency doubling
III–V semiconductor	Red and near IR	Tuning range small for any one device; tuning may be discontinuous
Lead salt semiconductor	Far IR	Expensive and cryogenic
Solid state vibronic laser	UV to near IR	Range includes frequency doubling
Optical parametric oscillators	Visible and IR	Needs pump laser
Nonlinear effects using variable-wavelength driver	UV, visible, IR	Needs tunable laser pump
Free electron laser	UV to millimeter wave	Large and very expensive

described earlier, a FEL represents a very large investment and probably will not be appropriate for routine spectroscopic applications.

Table 4-2 summarizes the most commonly used tunable lasers and their ranges of operation. In conclusion, a variety of tunable lasers are available with a broad variety of characteristics, and covering the wavelength range from the ultraviolet far into the infrared.

References

[1] N. Nakayama, *et al.*, *Japanese J. Appl. Phys.* 32, L54 (1993).
[2] D. C. Nguyen, *et al.*, Paper CThN1, 1993 Conference on Lasers and Electro-Optics, Baltimore, MD, May 2–7, 1993.
[3] D. L. Matthews, *et al.*, *Phys. Rev. Lett.* 54, 110 (1985).
[4] B. Arkinson, *et al.*, Paper CThO6, 1993 Conference on Lasers and Electro-Optics, Baltimore, MD, May 2–7, 1993.

Selected Additional References

C. A. Brau, *Free-Electron Lasers*, Academic Press, San Diego, 1990.
F. J. Duarte, ed., *Tunable Laser Applications*, Marcel Dekker, New York, 1995.
J. Hecht, *The Laser Guidebook*, 2nd ed., McGraw-Hill, New York, 1992.