Weber, M. J. “Introduction”
Handbook of Laser Wavelengths.
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Section 1: Introduction

Section 1

INTRODUCTION

The laser has become an invaluable tool for mankind. The ubiquitous presence of lasers in our lives is evident from their use in such diverse applications as science and engineering, communications, medicine, manufacturing and materials processing, art and entertainment, data processing, environmental sensing, defense, energy, astronomy, and metrology. It is difficult to imagine state-of-the-art physics, chemistry, biology, and medicine research with-out the use of radiation from various laser systems.

Laser action occurs in all states of matter—solids, liquids, gases, and plasmas. In this volume lasers are categorized based on the active medium. The spectral output ranges of solid, liquid, and gas lasers are shown in Figure 1.1 and extend from the soft x-ray and extreme ultraviolet regions to millimeter wavelengths, thus overlapping masers. In addition to lasers operating at one or more discrete wavelengths, some are tunable over broad wavelength bands. Using various frequency conversion techniques—harmonic generation, parametric oscillation, sum- and difference-frequency mixing, and Raman shifting—the wavelength of a given laser can be extended to longer and shorter wavelengths. Frequently a laser is used as an excitation source for a second medium that generates new laser wavelengths. The medium in essence acts as a wavelength shifter.

Within each category of lasing medium there may be differences in the nature of the active lasing ion or center, the composition of the medium, and the excitation and operating techniques. For some lasers, the periodic table has been extensively explored and exploited; for others—solid-state lasers in particular—the compositional regime of hosts continues to expand. In the case of semiconductor lasers the ability to grow special structures one atomic layer at a time by liquid phase epitaxy, molecular beam epitaxy, and metal-organic chemical vapor deposition has led to numerous new structures and operating configurations, such as quantum wells and superlattices, and to a proliferation of new lasing wavelengths.

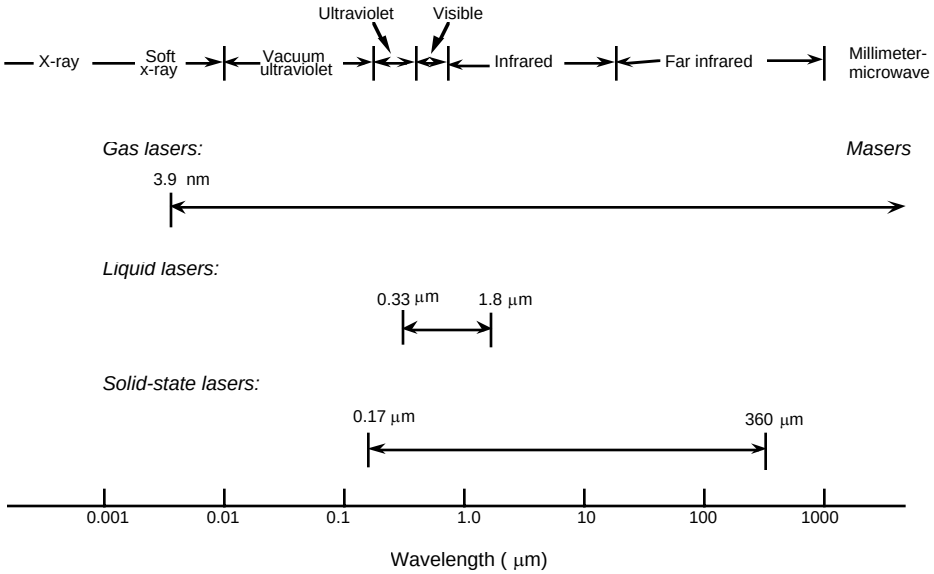

Figure 1.1 Reported ranges of output wavelengths for various laser media.

As will be evident from the brief descriptions below of the different types of lasers covered in this volume, the vitality of the field of lasers is stunning. Furthermore, recent announcements such as those of a single-atom

laser,[1] lasing without inversion,[2] and the use of Bose-Einstein condensates for an atom laser[3] continue to extend our understanding of atomic coherence and interference effects in laser physics and quantum optics.

Solid State Lasers

This group includes lasers based on paramagnetic ions, organic dye molecules, and color centers in crystalline or amorphous hosts. Semiconductor lasers are also included in this section because they are a solid state device, although the nature of the active center—recombination of electrons and holes—is different from the dopants or defect centers used in other lasers in this category. The recently emerging field of conjugated polymer lasers is also covered in this section. Solid-state excimer lasers, for which the number of reported cases of lasing is insufficient to warrant a tabulation, are noted at the end of this section.

Reported ranges of output wavelengths for various types of solid-state lasers are shown in Figure 1.2. The differences in the ranges of spectral coverage arise in part from the dependence on host properties, in particular the range of transparency and the rate of nonradiative decay due to multiphonon processes.

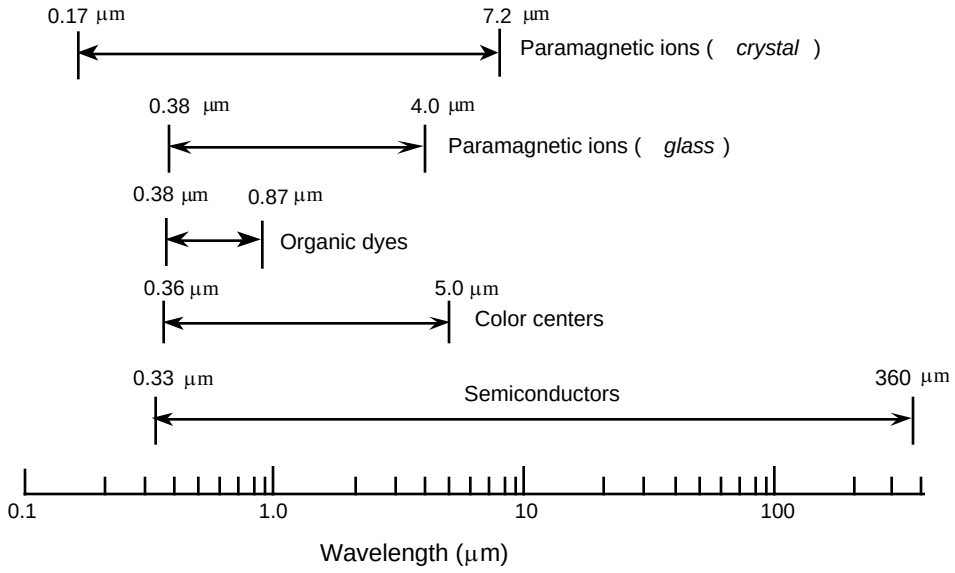

Figure 1.2 Reported ranges of output wavelengths for various types of solid state lasers.

Crystalline Paramagnetic Ion Lasers

The elements that have been reported to exhibit laser action as paramagnetic ions (incompletely filled electron shells) in crystalline hosts are indicated in the periodic table of the elements in Figure 1.3. These are mainly transition metal and lanthanide group ions. Also included are several elements (in italics) for which only gain has been reported (see Table 2.1.3). Typical concentrations of the lasing ion are ≤1%, however for some hosts and ions concentrations up to 100%, so-called stoichiometric lasers, are possible.

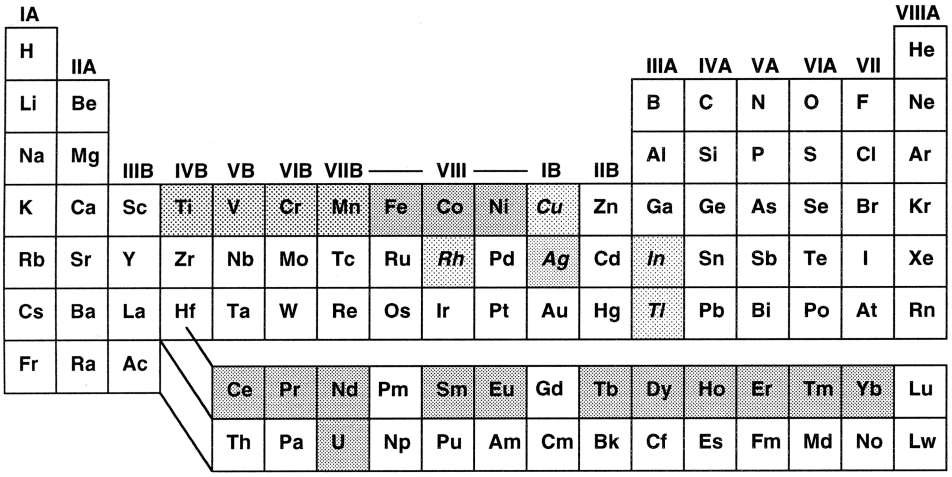

Figure 1.3 Periodic table of the elements showing the elements (shaded) that have been reported to exhibit laser action as paramagnetic ions in crystalline hosts. Gain has been reported for elements shown in italics.

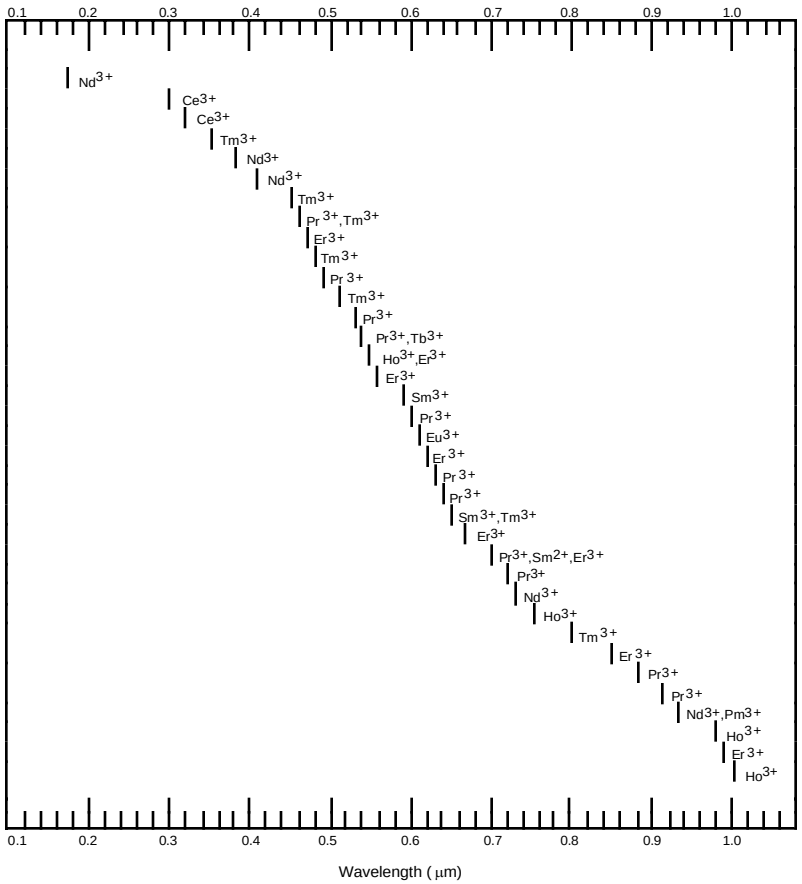

Figure 1.4a Approximate wavelengths of crystalline lanthanide-ion lasers; exact wavelengths are dependent on the host and temperature and the specific Stark levels involved (see Table 2.1.4).

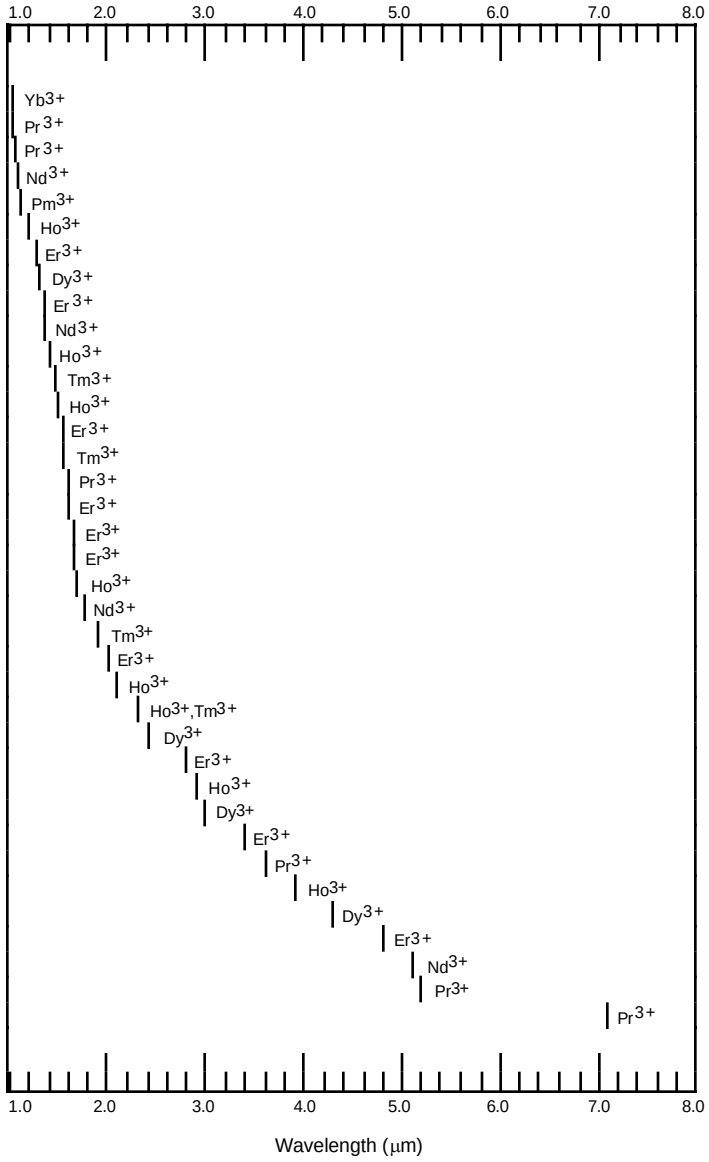

Figure 1.4b Approximate wavelengths of crystalline lanthanide-ion lasers; exact wavelengths are dependent on the host and temperature and the specific Stark levels involved (see Table 2.1.4).

The general operating wavelengths of crystalline lanthanide-ion lasers are given in Figure 1.4 and range from 0.17 μm for the 5d→4f transition of Nd^{3+} to 7.2 μm for the 4f→4f transition
transition between J states of Pr^{3+}. Whereas f→f transitions of the lanthanide ions have narrow linewidths and discrete wavelengths, d→f transitions of these ions and transitions of many iron group ions have broad emission and gain bandwidths and hence provide a degree of tunability. The tuning ranges of several paramagnetic laser ions in different hosts are shown in Figure 1.5; the ranges for explicit host crystals are included in Table 2.1.4. As evident from Figure 1.5, tunable lasers are based almost exclusively on iron transition group elements. Whereas narrow emission lines of Cr^{3+} in Al_2O_3 (ruby) were used for the first demonstration of laser action, broadband emissions of divalent, trivalent, and tetravalent chromium now provide tunable laser radiation throughout much of the 0.7 to 2.5 μm region.

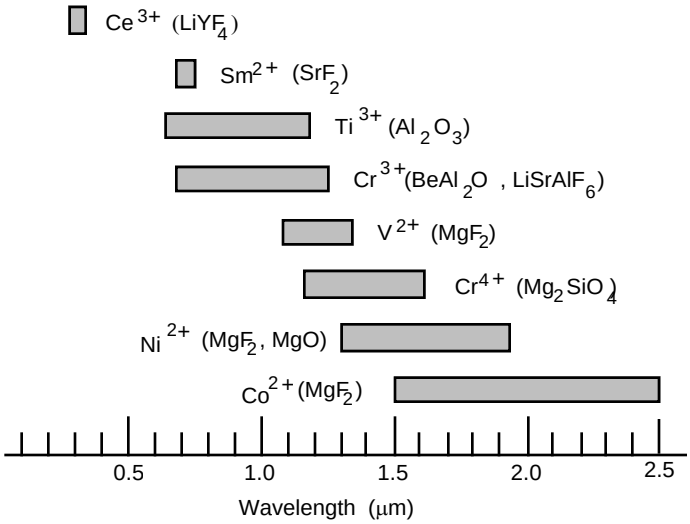

Figure 1.5 Reported wavelength ranges of representative tunable crystalline lasers operating at room temperature (see Table 2.1.4 for details).

Over 300 ordered and disordered crystals have been used as hosts for laser ions.[4] These include oxide, halide, and, recently, chalcogenide compounds. That so many different crystals of sufficient size and quality necessary to demonstrate laser action have been prepared is testimony to the crystal growers' art and capabilities. Codopant ions are sometimes added to the hosts to improve optical pumping efficiency. These sensitizer ions are included in Table 2.1.4.

The field of solid state lasers is large and still amazingly vital. These lasers have been operated pulsed, Q-switched, mode-locked, or cw. Picosecond pulses can be obtained from broadband lasers using various mode-locking techniques; femtosecond pulses can be obtained using saturable absorbers. The population inversion necessary for laser action in solid-state lasers has been achieved by optical pumping with flashlamps, cw arc lamps, the sun, or other lasers (electron beam pumping has also been reported). Recent advances in diode laser pumping now provide all solid-state devices that are rugged, compact, and have long lifetimes. As a result, diode-pumped solid-state lasers combined with nonlinear crystals are replacing gas and liquid dye lasers in a number of applications.

Upconversion, a concept promoted initially in the late sixties for phosphor displays and demonstrated for solid state lasing in 1971,[5] has witnessed a rebirth of interest with the resurgence of diode pumping and has made possible many new lasing transitions and excitation schemes.[4]

With one or more pulsed lasers as the pumping source, one can establish a population inversion between almost any pair of energy levels of interest and, provided excited state absorption is not dominant, lasing should be achievable, although the result may be neither efficient nor practical. In the case of the thirteen trivalent lanthanide ions, there are 1639 free-ion J states and 192,177 possible transitions between them, yet to date less than 70 have been used, thus one may anticipate the demonstration of many additional lasing transitions and hosts.

Glass Lasers

The past two decades have also witnessed increased activity in glass lasers, both in the form of bulk materials and of fiber and planar waveguides. The former include large neodymium-doped glasses for amplifiers used in lasers for inertial confinement fusion research. Fibers, with their long interaction region, and heavy metal fluoride glasses, with their low vibrational frequencies and hence reduced probabilities for decay by nonradiative processes, have made possible many new lasing transitions and operation at longer wavelengths. These include erbium- and praseodymium-doped fibers for telecommunications and erbium- and thulium-doped lasers for medical applications. Upconversion techniques have also been actively exploited for glass lasers.

The wavelengths of glass lasers are shown in Figure 1.6. The wavelength range is less than that of crystals at both the long and short wavelength extrema. The lasing wavelength could be extended to shorter wavelengths using glassy hosts with larger energy gaps such as beryl-lium fluoride and silica. Extension further into the infrared is limited by the vibrational frequencies associated with the glass network formers and nonradiative decay processes.

Unlike crystals, which have a unique composition and structure, changes in glass network formers (e. g., silicate, phosphate, borate) and network modifier ions (e. g., alkali, alkaline earths) affect the stimulated emission cross sections, rates of radiative and nonradiative transitions, crystalline field splittings, and inhomogeneous broadening.[6] Although trivially small compositional changes might technically constitute a new host material, those listed in Table 2.2.3 are generally characterized by either different compositions or different operating properties. Commercial glasses are identified by their company's designation. The glass type is generally known but the detailed compositions are usually proprietary.

Because of site-to-site variations in the local fields in glass, there is a distribution of energy levels and transition frequencies which appear as inhomogeneous broadening and provide tunability. In the small signal regime, laser action can be obtained by tuning across the inhomogeneous linewidth, whereas in the large signal or saturated gain regime spectral hole burning may occur. Examples of reported tuning ranges of lanthanide-ion glass lasers are shown in Figure 1.7.

Solid State Dye Lasers

Lasing media based on fluorescing organic dyes may be in the form of solids, liquids, or gases. Although the liquid state is the most familiar and commonly used form, numerous dye-doped solid materials have been reported to lase or exhibit gain in a spectral range extending from the near ultraviolet (376 nm) to the near infrared (865 nm). As shown in Table 2.3.1, a wide diversity of host materials have been utilized. These include various plastics and polymers, organic single crystals, and organic and inorganic glasses. Solid state dye lasers also include—in a somewhat more exotic vein—edible lasers[7] and lasing in animal tissue.[8]

Although the first reports of solid state dye lasers date back to the 1960s, photo-degradation of the dye has been a serious limitation to the utilization of these lasers. Recently there has been a revival of interest in these lasers, principally because materials exhibiting useful lifetimes and tunable laser action have been identified. A solid state dye laser is now offered commercially (see Table 6.1.1).

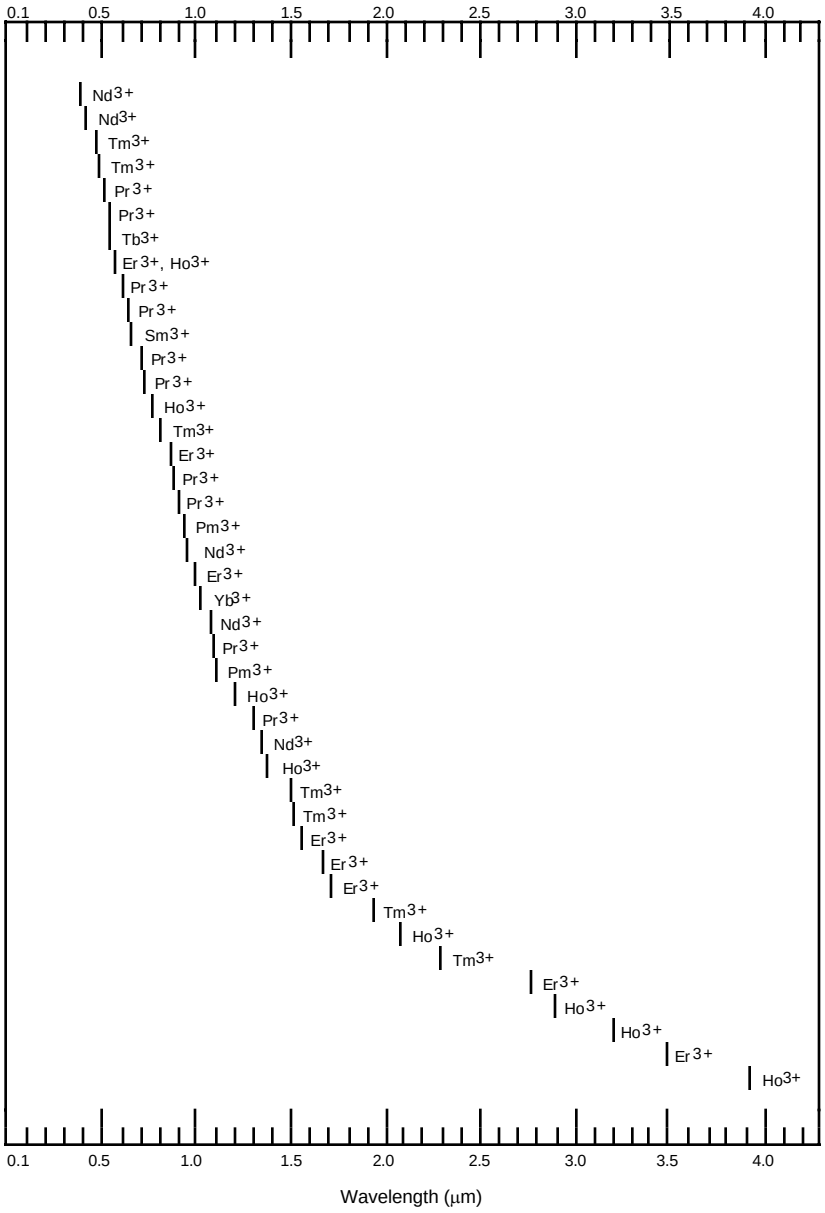

Figure 1.6 Approximate wavelengths of lanthanide-ion glass lasers; exact wavelengths are dependent on the glass composition and temperature and the specific Stark levels involved (see Table 2.2.3).

Color Center Lasers

Color center lasers have been reported that operate in the wavelength range from approximately 0.4 to 5 μm. The optically active centers in these lasers are various types of point defects (i. e., color centers) in alkali halide and oxide crystals. The color centers are

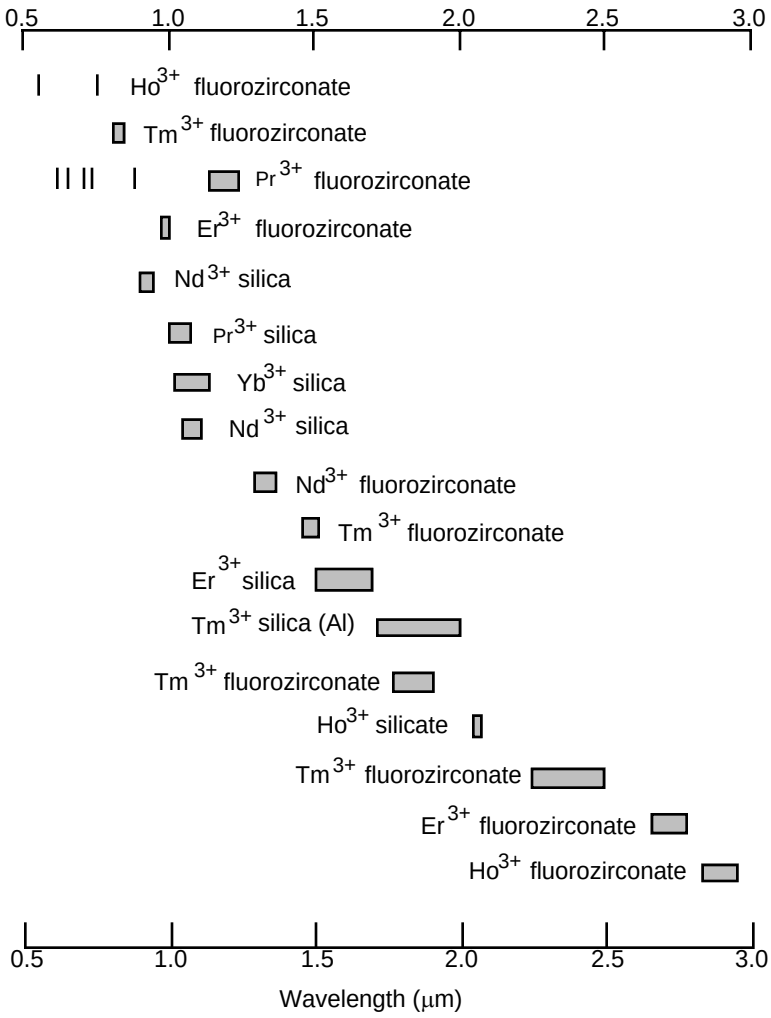

Figure 1.7 Reported tuning ranges of lanthanide-ion glass lasers (see Table 2.2.3).

generally produced by ionizing radiation or are thermally induced. Additional ions may be present to stabilize the defect center and are included in the description of the active center in Table 2.4.1. Other lasers in this category are based on vibrational transitions of molecular defects, such as CN^-.

Color center lasers are usually excited by optical pumping with broadband or laser radiation. Lasing involves allowed transitions between electronic energy levels, hence the gain can be high. Due to their large homogeneous emission bandwidths, color center lasers have varying degrees of tunable. The tuning ranges of some of the longer-lifetime color center lasers are shown in Figure 1.8.

The output of color center lasers may be cw or pulsed. As in the case of paramagnetic ion lasers, picosecond pulses can be obtained using various mode-locking techniques and femtoseconds pulses using saturable absorbers. The operative lifetimes of the color centers in these lasers depend on the temperature and can vary from hours to months. Many color center lasers require operation at low temperatures.

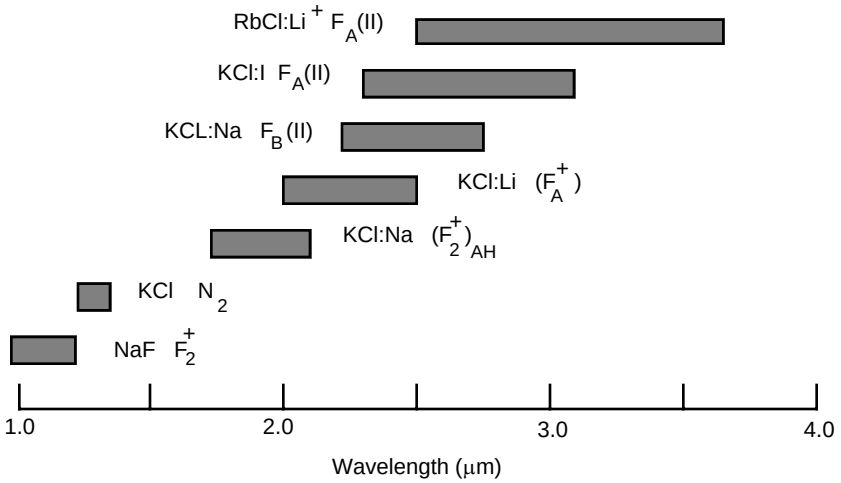

Figure 1.8 Reported tuning ranges of representative color center lasers (see Table 2.4.1).

Semiconductor Lasers

Laser action in semiconductor diode lasers, in contrast to other solid state lasers, is associated with radiative recombination of electrons and holes at the junction of a *n*-type material (excess electrons) and a *p*-type material (excess holes). Excess charge is injected into the active region via an external electric field applied across a simple *p*-*n* junction (homo-junction) or in a heterostructure consisting of several layers of semiconductor materials that have different band gap energies but are lattice matched. Heterostructure enables highly efficient radiative recombination of electrons and holes by confining them into the smaller band gap material sandwiched between higher band gap materials. This has been the most important step in achieving cw operation of diode lasers at room temperature. Excitation of semiconductor lasers has also been achieved by optical pumping and electron beam pumping.

The ability to grow special structures one atomic layer at a time by liquid phase epitaxy (LPE), molecular bean epitaxy (MBE) and metal-organic chemical vapor deposition (MOCVD) has led to an explosive growth of activity and numerous new laser structures and configurations. When dimensions become <100 nm, quantum effects enter that modify the band gap. Quantum wells result from confinement in one dimension, quantum wires from confinement in two dimensions, and quantum dots or boxes from confinement in three dimensions. The wavelength of quantum well lasers can be changed by varying the quantum well thickness or the composition of the active material. If materials of different lattice constants are used, thereby effectively straining the materials, one can further engineer the band gap. Strain-layer technology has led to combinations of various direct band gap materials which have extended the laser wavelength possibilities.

The lasing material may be elemental, but more generally is a compound semiconductor. Figure 1.9 shows the elements that have been used as constituents to achieve laser action in elemental and compound semiconductor materials.

The wavelength ranges of various types of semiconductor lasers are shown in Figure 1.10. III-V compound lasers, including antimonide-based III-V compounds, emit in the visible and the near- and mid-infrared regions. II-VI compound lasers generally emit at shorter wave-

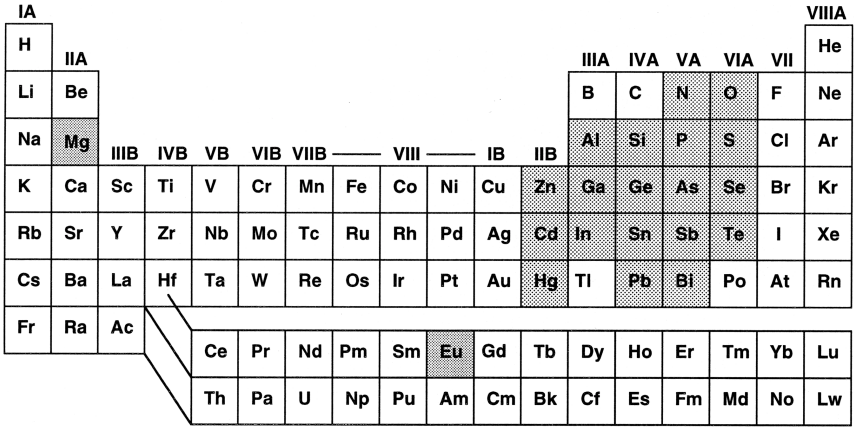

Figure 1.9 Periodic table of the elements showing the elements (shaded) that have been components of semiconductor laser materials.

lengths; mercury-based II-VI compounds extend the coverage over the range 1.9–5.4 μm. Longer wavelength diode lasers are based on IV-VI compounds (lead salts) and can be tuned by changing the temperature or current. The wavelength of quantum cascade lasers, unlike that of diode lasers, is determined by the active layer thickness rather than the band gap of the material. Multiple quantum well lasers have been tailored to operate in the range ~3–13 μm, thereby extending the range of III-V compound lasers. Germanium intervalence band lasers have thus far been operated in the range 75–360 μm.

In edge-emitting lasers the light output is in the plane of the gain medium; in surface-emitting lasers the light output is normal to the axis of the gain medium. The lasing wavelength is determined by the equivalent laser cavity thickness which can be varied by changing the thickness of either the wavelength spacer or the distributed Bragg reflector layers. Vertical-cavity surface-emitting lasers (VCSELs) can be prepared in two-dimensional arrays of independently modulated lasers.

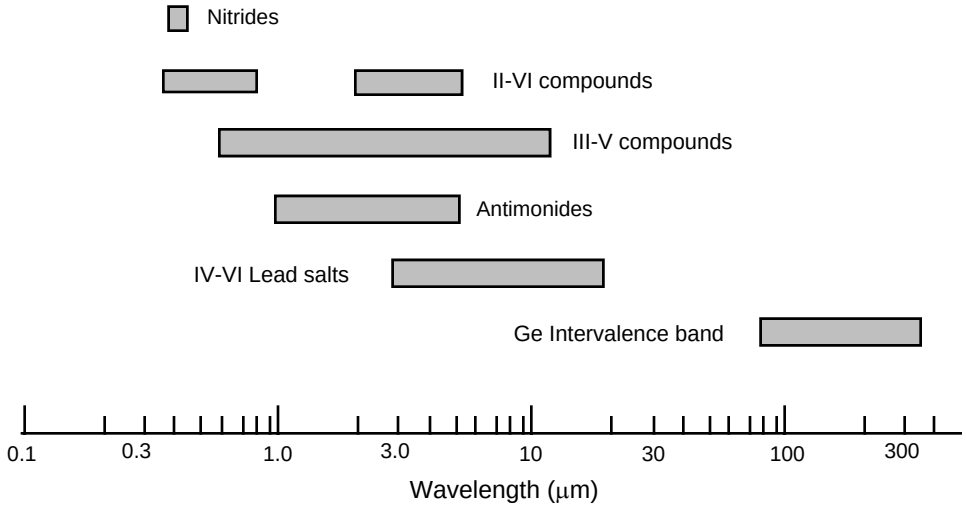

Figure 1.10 Reported ranges of output wavelengths of various types of semiconductor lasers (see Table 2.5.1).

The many different geometries of semiconductor lasers have spawned a proliferation of abbreviations and acronyms for the resultant laser structures, for example, BVSIS (buried V-groove substrate inner strip),

GRINSCH (graded-index separate confinement heterojunction) and SELDA (surface emitting laser diode array). Numerous additional terms used to describe semiconductor laser structures are defined in Appendix I.

Because it is possible to vary the constituent elements and tailor the laser emission, the wavelength of semiconductor lasers is a less fundamental property than for other lasers involving transitions between specific atomic levels. Thus the tabulation in Table 2.5.1 includes early pioneering papers and representative examples of different structures and operating conditions rather than an exhaustive listing of all reported semiconductor lasers.

Polymer Laser

Recently a new class of solid-state laser materials based on conjugated polymers has been the subject of increasing activity.[9] Unlike the dye-doped organic solid-state lasers covered in Section 2.3, the active media for these lasers are neat, undiluted, highly purified polymers. These materials have broad optical bands with large cross sections, high radiative quantum efficiencies, and large Stokes shifts of the absorption and emission bands, thereby providing the potential for high-gain, tunable laser action. Transient gain narrowing has been observed in optically pumped neat films of conjugated polymers with the aid of simple planar waveguiding structures or microcavities. The reported observations in Table 2.6.1 are indicative of lasing or amplified spontaneous emission. Thus far all experiments have involved pulsed optical excitation with the material are room temperature. These lasers have operated over a modest wavelength range from 390 to 640 nm.

Electroluminescence is a well-known property of conducting conjugated polymers. The question remaining—the holy grail—is whether it is possible to demonstrate an electrically driven polymer injection laser.

In addition to the pure polymer lasers above and the dye-doped polymer lasers in Section 2.3, amplified spontaneous emission has recently been reported from a Nd^{3+}-doped polymer optical fiber [poly(methyl methacrylate)].[10]

Excimer Lasers

Using matrix isolation techniques, it is possible to grow large, doped, rare-gas crystals. Xenon fluoride molecules can thus be formed by photodissociation of F_2 in Xe-F_2-Ar crystals. Optically pumped solid-state excimer laser action has been reported for XeF in Ar crystals at 286, 411, and 540 nm and for XeF in Ne crystals at 269 nm.[11-13]

Liquid Lasers

Organic Dye Lasers

The most common and familiar liquid lasers are those based on strongly absorbing organic dye molecules in an organic solvent involving allowed transitions of conjugate π electrons. By the selection of the active dye and solvent, laser action spanning a wavelength range from the near-ultraviolet through the near-infrared has been achieved. Laser action has been reported for over 500 different dyes in Table 3.1.1 and extends over a range from 0.336 to 1.8 microns. General categories of dyes and their spectral ranges are shown in Figure 1.11.

Because of the coupling of the electron with molecular vibrations, fluorescing dye emission occurs over a broad wavelength band. The very broad emission and gain spectra of organic dyes lead to tunable laser output—typically over several tens of nanometers. Because of this property, dye lasers are used extensively in

wavelength-selective spectroscopy. Tuning curves for various commercial dyes and pumping sources are shown in Section 6.3.

Dye lasers are excited either by linear or coaxial cylindrical flashlamps or other lasers and can be operated in either pulsed, mode-locked, or cw modes. The broad bandwidth of dye lasers is used to advantage in mode-locking schemes to generate ultra-short pulses with durations extending down to a few femtoseconds.

In addition to standard dye laser configurations, organic dye laser action in strongly scattering media consisting of titania nanoparticles in solution has been reported.[16] Lasing from dye-doped micrometer-size liquid droplets[17,18] and from evaporating layered microdroplets in the form of a glass core covered by liquid of dye in solution[19] has also been observed.

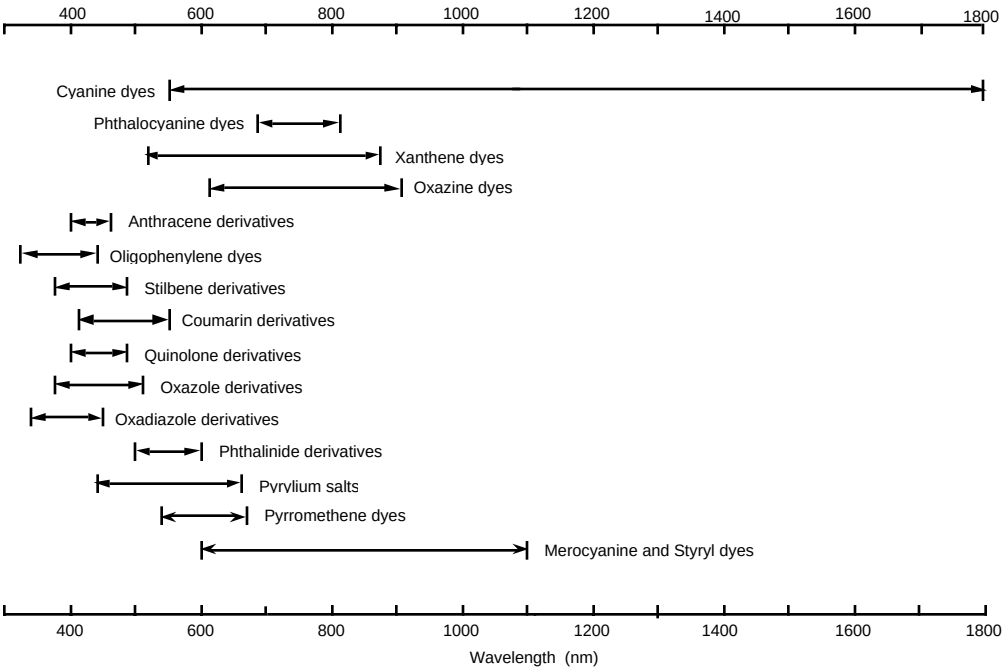

Figure 1.11 Reported ranges of output wavelengths of various types of organic dyes used in liquid lasers (adapted in part from reference 15).

Rare Earth Lasers

Liquid lasers based on lanthanide ions rather than organic molecules have been of two types. In rare-earth chelate lasers, the rare earth is complexed with a chelating agent. Optical pump energy is absorbed by the chelating ligand and transferred to the rare earth ion. Because high frequency vibrations of the organic molecules can give rise to nonradiative quenching of the rare earth fluorescence, only a few ions of the lanthanide series (Nd^{3+}, Eu^{3+}, Tb^{3+}) have been successfully used for this type of laser. These lasers are tabulated in Table 3.2.1

To reduce fluorescence quenching due to vibrations of the ion environment, rare earths have also been incorporated into inorganic aprotic solvents (no hydrogen anions). Thus far these have been oxyhalides or halides of the heavier elements such as phosphorous, sulfur, selenium, zirconium, tin, etc. Neodymium has been the active laser ion although other ions could undoubtedly be used. Neodymium aprotic liquid lasers and amplifiers have been operated in various pulsed modes; operating wavelengths are given in Tables 3.2.2 and 3.2.3. Because of the toxic and corrosive nature of most of these materials, these lasers have found little practical application.

Gas Lasers

Of the spectral ranges for lasers shown in Figure 1.1, by far the largest range is that of gas lasers. The number of elements reported to exhibit laser action in the gas phase has reached 53 and are indicated on the periodic table shown in Figure 1.12. The number of gas laser wavelengths is especially large, totaling more than twelve thousand.

Gas lasers may be categorized as atomic, ionic, or molecular and can be further divided or characterized by the nature of the transitions involved in the stimulated emission process; that is, the transitions may be between electronic, vibrational, or rotational energy levels.

In Figure 1.13 the extremes of the wavelength ranges of different types of gas lasers are shown. The rare gas halide, carbon dioxide, and short-wavelength (200–350 nm) ion lasers are still the dominant sources in their respective wavelength ranges, however, the use of gas lasers is being challenged by the compactness, reliability, efficiency, tunability, and spectral

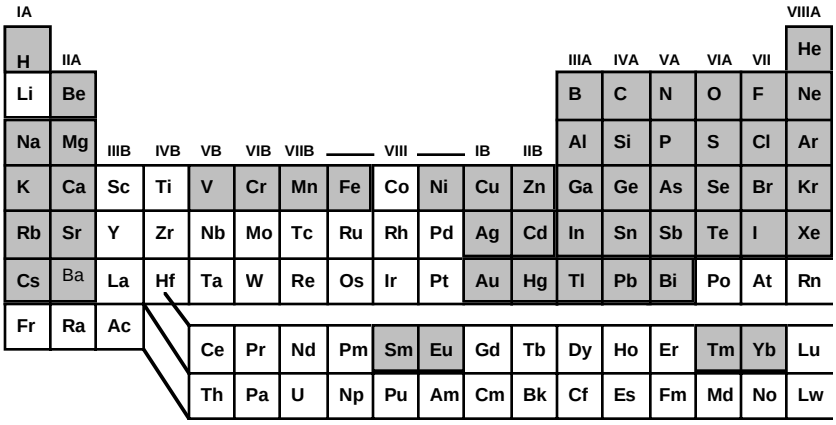

Figure 1.12 Periodic table of the elements showing those atoms or ions (shaded) that have been reported to exhibit laser action in the gas phase.

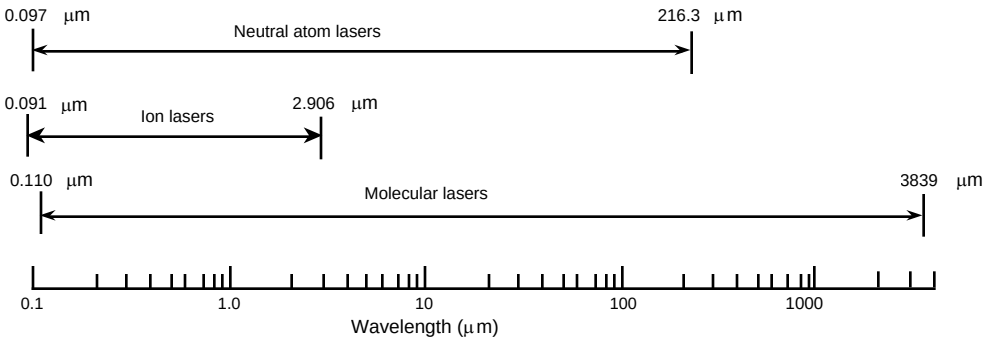

Figure 1.13 Reported ranges of output wavelengths of various types of gas lasers (excluding soft x-ray and far infrared lasers).

quality of all-solid-state lasers, notably in the spectral range between 0.5 and 3 μm. For very short wavelengths, however, only gaseous or plasma sources are possible because of the approximate 100-nm transparency limit of solids.

Gas lasers have been pumped by a variety of processes, several of which are not available for other laser media: (1) direct electron impact, (2) excitation transfer from an ion or an excited atomic or molecular species, (3) highly exothermic chemical reactions, and (4) optical excitation. All have yielded examples of efficient systems and are partially responsible for the wide array of gas lasers that are available. Vacuum ultraviolet and ultraviolet lasers originate from states having short lifetimes and hence are generally pulsed lasers. Optical pumping is used extensively for molecular lasers operating in the mid- to far-infrared regions where CO_2 or other powerful molecular lasers are used for excitation. Far-infrared (FIR) lasers operate cw or quasi-cw and they are used in numerous applications.

Gas pressures range from those in conventional lasers, measured in Torr, to the near vacuum of free electron lasers and of planetary atmospheres and interstellar space (natural lasers), to the high-density, high-temperature plasmas of x-ray lasers. These latter lasers are discussed in Section 5: Other Lasers.

Gas lasers covered in Section 4 are divided into two sections: one on neutral atom, ion, and molecular lasers and one on optically pumped far infrared and millimeter wave lasers. In doing this one must decide on a definition of "far infrared". A perusal of numerous texts and handbooks will reveal a variety of definitions beginning at 10 to 25 μm and extending to 300–1000 μm. Here we use 20 μm as the lower limit for the far infrared. By so doing we avoid the task of separating out the extremely numerous CO_2, N_2O, and other laser transitions in the 10–20 μm region that may be optically pumped. (Others have skirted this issue by using the term "submillimeter" and beginning the tabulations at 10 μm, but omitted the extremely numerous CO_2 and N_2O transitions in the 10 μm region.)[20] We have extended the tabulations of lasing transitions to wavelengths of a few millimeters, thus overlapping millimeter wave masers. It should be noted that the section on neutral atom, ion, and molecular lasers also includes a number of molecular gas lasers that are optically pumped.

Neutral Atom, Ionized, and Molecular Gas Lasers

The wavelength range of neutral atom, ionized, and molecular gas lasers extends from the vacuum ultraviolet through the submillimeter region. (Extreme ultraviolet and soft x-ray lasers are covered separately in Section 5.1.) Individual gas lasers may lase at several different wavelengths and have narrow spectral linewidths. The

output of argon lasers, for example, may consist of more than 30 lines of varying intensities from 275 to 686 nm. Neutral atom lasers emit in the visible and near infrared. Ion lasers emit in the ultraviolet and visible, the most important of which are based on the noble gas ions (argon, krypton, xenon). These are operated in various states of ionization and in either pulsed or cw modes.

Metal vapor lasers, which may be either neutral atoms or ions, emit in the near-ultraviolet and visible and operate either pulsed or cw. Of these, copper, gold, and lead are the most important examples with the first two being available commercially.

Excimer lasers are based upon the formation in the gas phase of transient molecules such as XeCl, ArF, KrF, most of which emit in the ultraviolet or vacuum ultraviolet. Produced by collisions between rare gas ions or neutrals in excited states and halogen-containing molecular precursors, these molecules have strongly bound upper laser levels but dissociative or weakly bound ground states. These diatomic molecules are generally produced in fast electrical discharges but can also be pumped optically or by intense electron or proton beams. Since the excited state lifetimes are short, ~10 ns, these lasers can emit powerful ultraviolet pulses of nanosecond duration.

Molecular lasers encompass a wide variety of molecules, operating conditions, and output wavelengths ranging from electronic transitions of the nitrogen (N_2) laser in the near ultraviolet, to the widely used vibrational-rotational transitions of the carbon dioxide (CO_2) laser in the mid-infrared, to the rotational transitions of various halide molecules lasing in the far infrared-submillimeter region. Electrically excited lasers such as H_2O, HCN, and DCN have transitions that extend well into the far infrared region.

In chemical lasers an inverted population is achieved by a chemical reaction (for example, the exothermic reaction of H_2 and F_2 to yield vibrationally excited HF). In the oxygen-iodine laser, excited oxygen transfers electronic energy to metastable levels of iodine. These lasers operate in the near to middle infrared and have been operated pulsed and cw. Several examples of chemical lasers are listed in Table 6.4.1.

The wavelengths of all of the above types of gas lasers are included in Table 4.1.1.

Optically Pumped Far Infrared and Millimeter Wave Lasers

These lasers are optically pumped by narrowband pump sources to excite molecules into a specific rotational state of an excited vibrational state and are usually operated cw or quasi-cw. Organic molecules used for far infrared and millimeter wave lasers now number more than one hundred, the most prominent ones being CH_3OH, $C_2H_2F_2$, and CH_3F. Combined with the use of several different isotopes and the possibility of transitions between many different vibrational and rotational levels, reported lasing transitions are now numbered in the thousands. The wavelengths of these transitions are given in Table 4.2.1. Pump transitions are not included in the table but can be found in the references cited in the introduction to the table.

Laser output powers depend not only on molecular properties but also on factors that vary with the design of the experiment. For those interested in the most intense far infrared and millimeter wave laser lines, a table of calibrated power measurements of over 150 lines between 40 μm and 2 mm having output powers of 1 mW or more is given in reference 20.

Optically pumped far infrared and millimeter wave lasers have found numerous applications in atomic and molecular spectroscopy, heterodyne sources for FIR spectroscopy, atmospheric spectroscopy, plasma diagnostics, and in frequency metrology connecting the microwave and visible regimes.

Other Lasers

Section 5 covers other types of lasers distinguished by their nature or specific characteristics, such as less conventional lasing configurations, extreme spectral regions, or specific operating conditions. In general they constitute many of the most interesting realms of lasing. Most are exploratory laboratory lasers rather than commercial lasers.

Extreme Ultraviolet and Soft X-Ray Lasers

In the decade since the first demonstration of lasing in the extreme ultraviolet (EUV) region, extensive efforts have been devoted to exploring lasing of various ions and in extending the wavelength range of laser action. Lasers have now been observed to operate from the extreme ultraviolet to well out into the soft x-ray region. (87.4 to 3.56 nm). These wavelengths are of particular interest for photolithography and biological imaging instrumentation. Progress in extreme ultraviolet lasers has been made possible in part by advances in multilayer techniques for producing the requisite optics for these wavelengths.

As shown in Figure 1.14, lasing has been reported for more than one-half of the elements in the periodic table. Lasing is achieved in highly ionized plasmas, generally produced by pulses from large, high-power lasers incident on solid targets, by electron collisional excitation from an ionic ground state into the upper laser level, or by sequential ionization followed by recombination into the upper laser level. Recently extreme ultraviolet lasing has

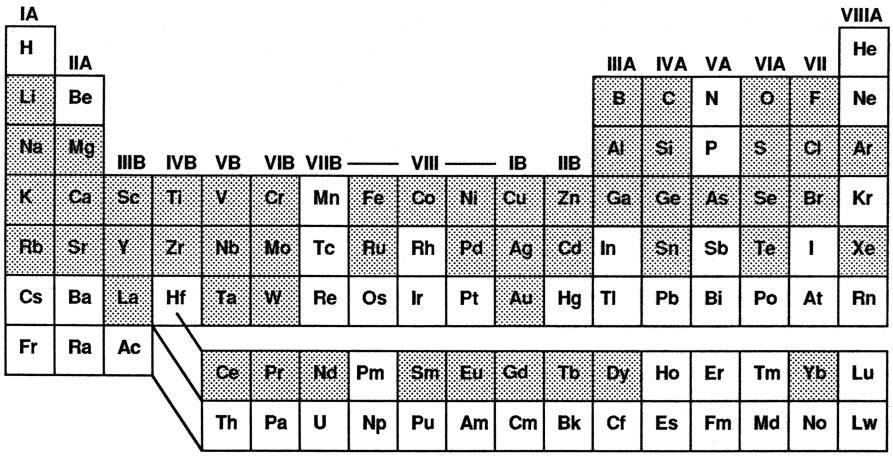

Figure 1.14 Periodic table of the elements showing the elements (shaded) that have been reported to exhibit laser action in the extreme ultraviolet and soft x-ray regions.

been reported from so-called table-top lasers in which fast electric excitation of the plasma is confined in a narrow capillary channel. The discharge plasma is formed by a low-induction, high-voltage current pulse.[21]

The electron configurations of the highly ionized states are similar to those of neutral atoms with the same number of electrons. Thus Al^{10+}, for example, which has only three electrons is described as "Li-like", Se^{24+} (with ten electrons) is described as "Ne-like", and Ta^{45+} (with 28 electrons) is described as "Ni-like". The wavelengths and transitions of extreme ultra-violet and soft x-ray lasers are given in Table 5.1.1.

Free Electron Lasers

Free electron lasers (FEL) provide laser radiation over a large wavelength range spanning six orders of magnitude—from the ultraviolet to millimeter waves (248 nm to 8 mm). They are based on a beam of high energy electrons traversing a spatially varying magnetic field (wigglers, undulators) which cause the electrons to oscillate and emit radiation. Because there is a continuum of states rather than discrete states as for atoms or molecules, a FEL is not a quantum device; almost all features of a FEL can be described classically.

Free electron laser configurations include (1) oscillators with reflectors at the ends of the magnet array, thus providing multi-pass, low-gain operation, (2) amplifiers in which electrons are injected into an undulator in synchronism with a signal derived from a conventional laser source, and (3) self-amplified spontaneous emission amplified by a single pass through a wiggler.

Various types of electron accelerators are used for FELs: storage rings, rf and induction linacs, electrostatic and pulse-line accelerators (operating in single-shot mode), microtrons, modulators, and ignition coils. RF linacs have been the dominant accelerator used. The wavelength ranges of FELs for different types of accelerators are shown in Figure 1.15. Storage rings provide the highest energy electrons and should be exploitable to achieve wavelengths of less than 100 nm.

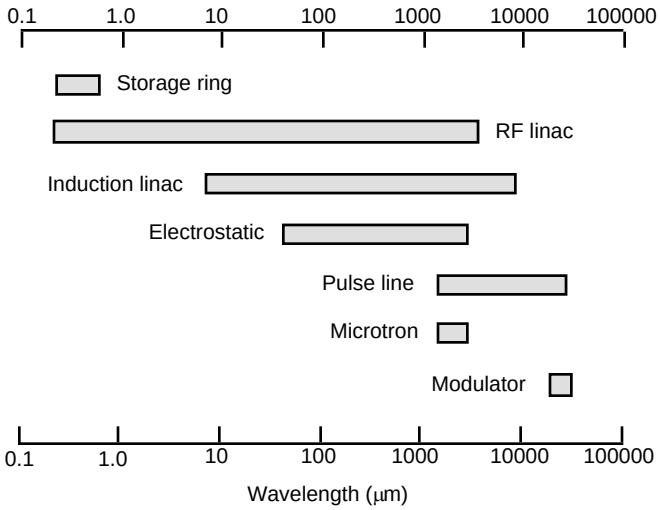

Figure 1.15 Reported ranges of output wavelengths of free electron lasers for various types of electron accelerators (see Table 5.2.1).

Flexibility of design and of operation configuration are characteristic of FELs. They can be operated both cw and pulsed with peak powers of ~1 GW. The spectral output is generally that of the Fourier transform of the optical pulse length. Because the resonance condition depends on the electron velocity component along the undulator axis and the wavelength range is determined by the energy range of the electrons, it is possible to build a continuous-ly tunable source. Such FELs are potentially useful for medical applications and condensed matter research. Current research and development is aimed at obtaining high average power with good overall efficiency, broad bandwidth, and in compact systems. There is also promising work in the area of designing an x-ray FEL.

Nuclear Pumped Lasers

Nuclear pumped lasers (NPL) are gas lasers excited directly or indirectly by high energy particles or gamma rays resulting from nuclear reactions (fission, fusion, radioisotope). This may occur either in a reactor or a

nuclear explosion, thus NPLs can be grouped into two broad categories: reactor pumped lasers and nuclear device pumped lasers. Both types provide direct conversion of nuclear energy to directed optical energy. Nuclear pumped lasers have been demonstrated to operate pulsed or steady-state over a wavelength range extending from the vacuum ultraviolet (173 nm) to the infrared (3 μm) using a variety of gases and molecules. These results are summarized in Table 5.3.1.

Natural Lasers

Naturally occurring maser action is frequently found in clouds of molecular gases in our galaxy where water or other molecules amplify radiation from stars. Whereas natural masers operating at microwave and millimeter wavelengths have been known for several decades and now number in the hundreds,[22,23] shorter wavelength natural lasers are much rarer. Those discovered thus far operate at infrared wavelengths of CO_2 in the mesosphere and thermo-sphere of Mars and Venus and, more recently, at the submillimeter wavelengths of hydrogen in interstellar and circumstellar sources. The tabulated data for these lasers in Table 5.4.1 are necessarily limited, however comprehensive references are provided.

Several years ago C. W. Townes made the thought provoking observation " . . . that if radio astronomy had been sponsored more strongly in the United States we probably would have discovered masers and lasers sooner. Masers could have been detected long ago in the sky—probably as early as the 1930s, and certainly immediately after or during World War II they could easily have been detected, but nobody was looking."[24]

Inversionless Lasers

It is possible to extract energy from a medium even if there are more atoms in the lower level than the upper level. Lasing without inversion (LWI) has been the subject of considerable interest in the past decade and although results to date are not extensive they are included in this volume for completeness. Two schemes, Λ and V, have been used to obtain gain. In the first scheme, the optical fields have a common upper level and LWI is achieved via a coherence between the two lower levels. In the V scheme, the fields have a common lower level and LWI is achieved via a coherence between two upper levels. Gain and cw laser oscillation have now been observed in metal vapors using both Λ and V schemes at wavelengths in the visible-near visible region. These experiments are summarized in Table 5.5.1.

Commercial Lasers

Of the over 15,000 lasing transitions reported in this volume and the many types of lasers that have been demonstrated, only a comparatively few lasers are available commercially. These include numerous gas lasers (noble gases, molecular gases, metal vapors, excimers), liquid lasers (using a multitude of organic dyes to cover the entire visible and near infrared spectral regions), and solid state lasers (paramagnetic ions in crystals and glasses, color centers, organic dyes, and semiconductor materials of various structures and configurations).

Commercial lasers are listed in order of increasing wavelength in Table 6.1 and include (1) gas lasers (atomic: helium-neon, helium-cadmium, ionic: Ar^+, Kr^+), excimer lasers (KrF, ArF, XeF, XeCl), molecular gas lasers (CO_2 and CO), metal vapor lasers (principally Cu and gold), and molecular lasers extending into the submillimeter and millimeter wavelength range, (2) solid state lasers of both lanthanide and iron group ions in crystals and glasses and color center lasers, (3) dye lasers using many organic dyes in liquid solvents, and (4) semiconductor lasers, both single-element and multi-element arrays.

General output properties of representative solid state, semiconductor, dye, and gas lasers are given in Tables 6.2.1, 6.3.1 and 6.4.1 respectively. These data are taken from recent (1995–1997) buyers' guides and manufacturers' literature and are representative rather than exhaustive. Also, performance figures may be

expected to change due to advances in technology. Ranges of output wavelengths of selected tunable lasers are shown in Figure 1.16.

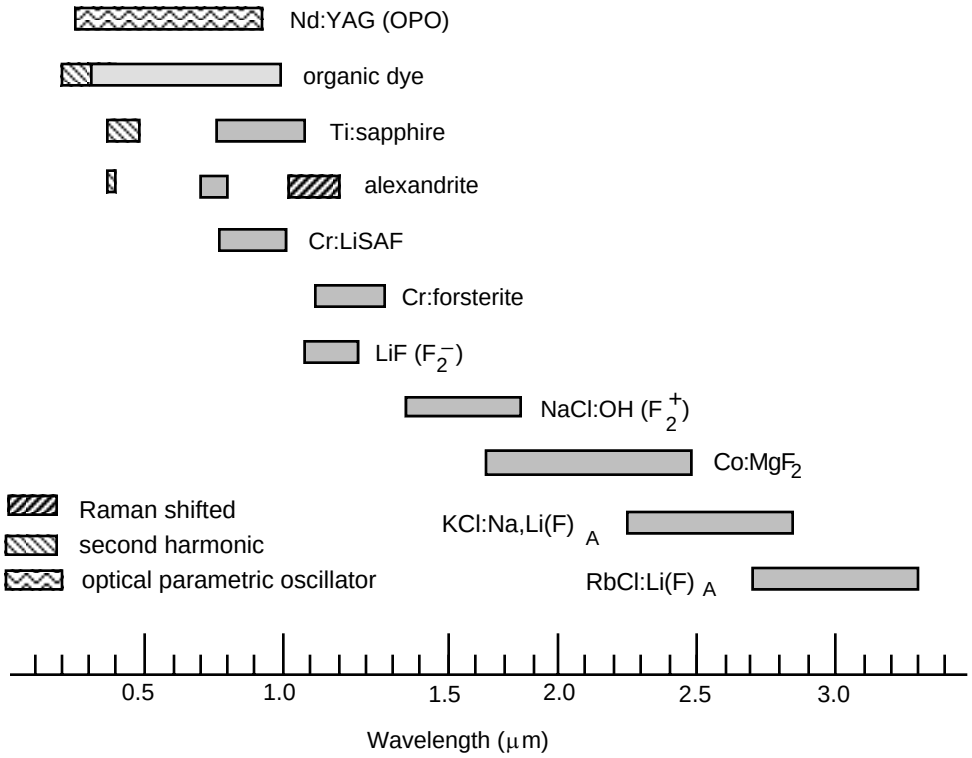

Figure 1.16 Ranges of output wavelengths of selected tunable commercial lasers (1995–1997 data).

Commercial lasers are now available with an astonishingly large range of properties—wavelengths from the ultraviolet through the infrared, pulse lengths from femtoseconds to microseconds to continuous wave, operating with predicted lifetimes in some cases of greater than 10^6 hours, highly monochromatic or tunable, and with peak powers of many joules and cw powers of tens of kilowatts. These lasers are used both for special research and for numerous commercial applications.

Because of their use in local and long distance communications, barcode readers, compact disk (CD) players for entertainment and computer applications, and as pump sources for solid-state lasers, the market quantities of semiconductor diode lasers (~10^8 units per year) generally are many orders of magnitude larger and unit prices are many orders of magnitude smaller than those for most gas or solid state lasers.

The market share of various categories of lasers can change with changing technology. Somewhat in the same way that the vacuum tube in electronics gave way to solid state transistors and integrated circuits, gas lasers—which have been predominant in many applications—are being replaced in a number of applications by all-solid-state lasers pumped by diode lasers.

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