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Solid-state lasers for medical applications

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Abstract: The goal of this chapter is to provide the fundamentals of solid-state lasers used in medical applications. After a brief introduction, the fundamental properties of solid-state laser active media are described. The main part of this chapter contains the description of a solid-state laser system, its pumping and cooling, modes of operation, and emission wavelength control, including a non-linear conversion of radiation. In the following part, a detailed description of selected solid-state laser types used in medical applications is given. At the end of this chapter, the construction and materials of some novel solid-state lasers are described.

Key words: solid-state lasers, non-linear conversion of radiation, laser crystal, diode pumping, Q-switching, tunable solid-state laser.

5.1 Introduction

Solid-state lasers (SSL) are attractive sources of coherent radiation for various scientific as well as industrial applications. As was mentioned in Chapter 2, lasers can be divided into five groups: solid-state, semiconductor, liquid, gas, and plasma lasers. According to the state of a laser active environment, solid-state and semiconductor lasers can be integrated into one group, because both these active media are in solid form. But, in a narrower sense of the term, solid-state lasers are systems whose active medium consists of a transparent solid matrix (e.g. crystal, glass or ceramics) doped by an optically active ion and using optical pumping for excitation.

Research into solid-state lasers has continued for more than 50 years. Gradually significant progress has been reached in obtaining new emission wavelengths and tunable sources of laser radiation. Also, the generation of ultrashort pulses and improving the efficiency and performance of solid-state lasers has been achieved. If the laser system has to be deployed outside the laboratory, a compact, easy-maintenance, break-resistant system is required. Solid-state lasers generally meet these criteria better than the corresponding gas or liquid lasers. Especially, a new generation of SSL systems – diode-pumped, fiber, slab and disc lasers – have begun a new era in the research and development of medical instruments due to the reduction of the size and consumption of energy. Nevertheless, for many applications the conventional powerful flashlamp laser systems are still used. Therefore, this section explains the basis of the construction of the SSL, gives the specification of the main, frequently used active media, and in the last part it describes the specific types of SSL: fiber, slab, disc, and microchip laser.

5.2 Solid-state laser active materials

The amplification and generation of radiation in SSL is based on stimulated transitions between energy levels of optical electrons bonded in electron shells of optically active ion dopants (activators) fixed in a solid-state matrix. The activator and matrix are the main components of the solid-state active material. As was explained in Chapter 2, the necessary condition for radiation amplification in active medium is an inverse occupation of energy levels (Fig. 2.3). The activator is excited by absorption of optical radiation. The creation of the population inversion of a solid-state active medium is based on the fact that, for a suitable combination of activator–matrix, the energy spectrum of such a system can contain levels whose ability to relax to the ground state after excitation is reduced. Such a level (or levels) is called metastable. If the activator ions, due to the pumping and other transitions, reach this state, they may remain there for a longer time than in other, non-metastable levels. This gives the possibility of creating a population inversion with respect to the lower-lying levels which do not have this property.

Generally speaking, the SSL-active medium is characterized, far more than other types of lasers, by a long lifetime of the upper laser level (from microseconds to milliseconds), which is usually much longer than the time necessary to achieve a population inversion (from nanoseconds to microseconds). Therefore, it is possible to reach inversion in active material, and even to accumulate the excitation energy stored in the population inversion levels for some time until it is appropriate to release it for the generation of laser radiation, as well as for its strengthening.

5.2.1 Laser-active ions in solids

The energy levels of the solid-state laser active medium are primarily determined by specific activator-ion additives. The spectroscopic properties of the active medium, which, in addition to the structure of energy levels, also reflect the probability of transitions between these levels, are then given by particular activator–matrix combinations, and may possibly be affected by external conditions such as temperature or pressure.

Ions of 19 elements (see periodic table in Fig. 5.1) have been successfully used to date for the generation of laser radiation with the help of a solid-state laser (Kaminskii, 1996; Sorokina and Vodopyanov, 2003). There are two main groups of ions: transition-metal ions from the iron group (Ti^{3+}, V^{2+}, Cr^{2+}, Cr^{3+}, Cr^{4+}, Mn^{5+},

1 H																	2 He
3 Li	4 Be											5 B	6 C	7 N	8 O	9 F	10 Ne
11 Na	12 Mg											13 Al	14 Si	15 P	16 S	17 Cl	18 Ar
19 K	20 Ca	21 Sc	**22 Ti**	**23 V**	**24 Cr**	**25 Mn**	**26 Fe**	**27 Co**	**28 Ni**	29 Cu	30 Zn	31 Ga	32 Ge	33 As	34 Se	35 Br	36 Kr
37 Rb	38 Sr	39 Y	40 Zr	41 Nb	42 Mo	43 Tc	44 Ru	45 Rh	46 Pd	47 Ag	48 Cd	49 In	50 Sn	51 Sb	52 Te	53 I	54 Xe
55 Cs	56 Ba	La-Lu	72 Hf	73 Ta	74 W	75 Re	76 Os	77 Ir	78 Pt	79 Au	80 Hg	81 Tl	82 Pb	83 Bi	84 Po	85 At	86 Rn
87 Fr	88 Ra	Ac-Lr	104 Rf	105 Db	106 Sg	107 Bh	108 Hs	109 Mt									

57 La	**58 Ce**	**59 Pr**	**60 Nd**	61 Pm	**62 Sm**	**63 Eu**	64 Gd	**65 Tb**	**66 Dy**	**67 Ho**	**68 Er**	**69 Tm**	**70 Yb**	71 Lu
89 Ac	90 Th	91 Pa	**92 U**	93 Np	94 Pu	95 Am	96 Cm	97 Bk	98 Cf	99 Es	100 Fm	101 Md	102 No	103 Lr

5.1 Periodic table of elements. SSL activators are highlighted.

Fe^{2+}, Co^{2+}, Ni^{3+}) and rare-earth ions from the lanthanides group (Ce^{3+}, Pr^{3+}, Nd^{3+}, Sm^{2+}, Sm^{3+}, Eu^{3+}, Tb^{3+}, Dy^{2+}, Dy^{3+}, Ho^{3+}, Er^{3+}, Tm^{2+}, Tm^{3+}, Yb^{3+}). In addition to these transition-metal elements and lanthanides, laser action has also been achieved with uranium U^{3+} ions. However, other actinoids, like uranium, are radioactive and have no stable isotopes.

Optical properties of activators are determined by electron configurations of valence shells. Within each of the two groups, atoms are located in the same row of the periodic table of elements, and therefore they have similar properties. Both groups, however, differ considerably among themselves. While the optically active electrons of transition ions are located on the border of the atom's electron shell in the 3d subshell, in the case of lanthanide ions the optically active valence electrons are located in the 4f subshell, which is shielded from the surroundings by the 5s and 5p subshells, containing electrons with lower energy but higher distance from the atom core, although broader than the core. Ions of transition elements are therefore exposed to the strong influence of the matrix, which can lead to broad absorption and emission bands and strong temperature dependence of the parameters of the active medium, while the transitions between levels in shielded lanthanide ions correspond to substantially narrower spectral lines (Durante, 1995; Powell, 1998; Svelto, 1998). An overview of laser properties of selected activators is shown in Table 5.1.

For the construction of solid-state lasers for industrial and medical applications, the greatest utilization has been achieved from the group of lanthanide ions: neodymium Nd^{3+}, erbium Er^{3+}, thulium Tm^{3+}, holmium Ho^{3+}, and ytterbium Yb^{3+}. From the group of transition-metal elements, chromium Cr^{3+}

Table 5.1 Laser properties of selected activators: approximate position of the emission and absorption lines and bands, and the lifetime of the metastable state

Activator	Emission regions (μm)	Absorption regions (μm)	Lifetime (μs)
Ti^3+	0.67–1.1	0.4–0.65	3.2
Cr^{2+}	1.8–3	1.6–1.9	4–13
Cr^{3+}	0.68, 0.7–1.1	0.38–0.42, 0.51–0.76	60–1500
Cr^{4+}	1.16–1.34	0.9–1.1	3
Nd^{3+}	0.9, 1, 1.3, 1.4, 1.8	0.54–0.58, 0.73–0.76, 0.80–0.81	50–800
Pr^{3+}	0.53, 0.6, 0.64, 0.69, 0.72	0.44, 0.47, 0.48, 0.59	10–60
Tm^{3+}	0.45, 1.8–2.1, 2.35	0.78–0.81	500–10 000
Ho^{3+}	0.55, 0.75, 0.98, 1.4, 1.5, 2.36, 2.9	0.48, 0.51, 0.98	15 000
Er^{3+}	0.5, 0.7, 0.85, 1.55, 1.66, 2.69–2.94	0.79, 0.97, 1.5	100–2000
Yb^{3+}	1.02–1.05	0.89–0.95	800–1300

Source: Kaminskii, 1996; Powell, 1998.

and titanium Ti^{3+} ions are mostly used in solid-state active media. They have broad gain line and are suitable for the construction of tunable lasers and ultrashort pulse generators.

In terms of further development of solid-state lasers for medical application, good prospects seem to be ions of praseodymium Pr^{3+}, whose emission spectrum is located in the visible spectral region (Richter *et al.*, 2004), and also ions of chromium Cr^{2+} or iron Fe^{2+}, enabling the construction of tunable lasers in the mid-infrared spectral region (Sorokina and Vodopyanov, 2003).

5.2.2 Laser host materials

The *matrix* of a laser active medium is a solid dielectric substance in which *activator* ions are placed and fixed. This substance determines most of the physical properties of the laser active medium (hardness, thermal conductivity, durability, etc.). The only exception is the spectroscopic properties of the active medium, which indicates the particular activator used. However, the effect of the matrix on the spectroscopic properties of the active medium cannot be neglected. A suitable choice of matrix can influence the laser operating wavelength, tunability, or the lifetime of the upper laser level.

In order to be usable as a matrix of solid-state laser active medium, a material must meet the following conditions. Especially, it is necessary that the matrix itself does not absorb radiation in the spectral regions used for laser pumping and generation or in which laser radiation takes place. It should not contain any inhomogeneities or defects which could lead to light scattering. Also important are the chemical stability of the matrix and its resistance

Table 5.2 Selected solid-state laser matrices and their characteristic thermal, mechanical and optical properties

Matrix	Thermal properties		Mechanical properties		Optical properties	
	Melting point (°C)	Heat conductivity ($Wm^{-1}K^{-1}$)	Young's modulus (GPa)	Fracture toughness ($MPa/m^{1/2}$)	Refractive index	*dn/dT* (10^{-6} K^{-1})
Crystals						
Al_2O_3	2040	34	405	2.2	1.76	+1.6
$Y_3Al_5O_{12}$	1970	13	282	1.4	1.82	+8.9
$LiYF_4$	820	5.8/7.2	75	0.3	1.63	–2.0/–4.3
$LiSrAlF_6$	766	3.1	108	0.3	1.41	–2.5/–4.0
Glass						
Q-246 (SiO_2)	(590)	1.36	92	0.83	1.57	+3.8
LG-760 (P_2O_5)	(545)	0.67	52	0.45	1.50	–6.8
Ceramics						
$Y_3Al_5O_{12}$	1930 ± 20	11.7	282	8.7	1.83	—

Source: Koechner, 1999; Meyers, 2002.

to mechanical and thermal stress. Matrix material must be accurately machined and, to become a widely used material, its production must be well technically mastered and economically acceptable. These conditions are met by some of the crystals, glass and ceramic materials. Examples of these materials are listed in Table 5.2.

Crystals

Crystals, or more precisely synthetic ion-doped single crystals of oxides or fluorides, are still the most common type of solid-state laser matrices. This group is also the largest one – hundreds of different synthetic crystals with an admixture of several of the above-mentioned ions were tested as solid-state laser active media in the first two decades after the discovery of the first laser (Kaminskii, 1981, 1996). This variety of solid-state lasers allows the required properties of this type of active medium to be provided using the appropriate matrix–dopant combination.

Ionic single crystals meet the requirements which have to be fulfilled by a solid-state laser matrix, thanks to a periodic arrangement of their internal structure and chemical nature of ion bonding. These characteristics result in good thermal conductivity, mechanical strength, and hardness, but also fragility and high melting point. A result of the ordered crystalline structure of this material is the anisotropy of its properties.

The pure ionic single crystals are transparent to electromagnetic radiation over a broad range of wavelengths. The activator ions are incorporated in the crystal lattice matrix in a position where they have constant and stable orientation, and in the first approximation all activators therefore contribute to the spectroscopic properties of the active medium in the same way.

The main drawback of crystals is the technologically demanding manufacture. Special methods of growing single crystals were developed, such as the Verneuil method, the Bridgman and Stockbauer method, or the method of zonal melting (Hurle, 1993; Uhrin, 2000). For industrial production of laser crystals, the most commonly used is the Czochralski method, in which a single crystal is pulled from its melt. In the case of oxides the melting temperatures may exceed 2000°C, and the use of special materials (iridium, molybdenum) is required for the melting crucible. About 1 mm crystal with a diameter of 80 mm can be grown per hour. The whole process of growing crystals takes several days. In spite of continuous technical development, it is quite difficult to get larger (more than 80 mm in diameter and 200 mm in length), optical-quality material with a homogeneous distribution of activators.

Glass

Glass is an amorphous isotropic solid material. It can be obtained by melting and subsequent cooling of a mixture of substances. During the cooling of the melt its viscosity increases such that it will be solidified without crystallization. The irregularity of the amorphous glass structure has substantial importance. The absence of crystal lattice has a negative impact mainly on the thermal conductivity, which is, in comparison with crystalline materials, very low. This limits the extractable mean laser power. Glass is also usually transparent over a narrower range than crystalline substance. The advantage of glasses over crystals, however, is their relative simplicity of manufacturing, maintaining good quality and the possibility of preparation of an almost unlimited variety of shapes and sizes.

Also, thanks to the irregular structure, a higher concentration of dopants can be dissolved in the glass without a negative influence on the mechanical properties of the glass. Because there are no significant positions or directions in the glass, the activator emission and absorption lines are, due to random effects, more widespread than in the case of a crystal matrix (Powell, 1998). The flexibility of the glasses, their amorphous structure, purity and homogeneity allow the drawing of long active optical fibers, which are the active medium of a fiber laser.

Ceramics

Ceramics are inorganic non-metallic materials with a heterogeneous structure consisting of crystalline and sometimes glass materials of various compositions and arrangements. They can be produced by sintering of components at a temperature lower than their melting point. Thanks to their features, the ceramics fall on the borderline between single crystals and glasses. Since the discovery of the laser principle, transparent ceramics were considered to be a promising solid-state matrix, but their actual use was prevented due to high losses. A significant improvement in the optical properties of ceramics was obtained by sintering nanocrystalline powders prepared from high purity raw materials by a chemical process. Ceramics, like glasses, are less sensitive to the concentration of active ions. In addition to the mechanical and optical properties of ceramics, these materials have the advantage that they can be used in the production of large blocks of the laser active medium. The suspension mixture of nanocrystalline powders can be directly cast into a mold and sintered after drying in a vacuum to produce the desired ceramic shape.

5.3 Solid-state laser systems

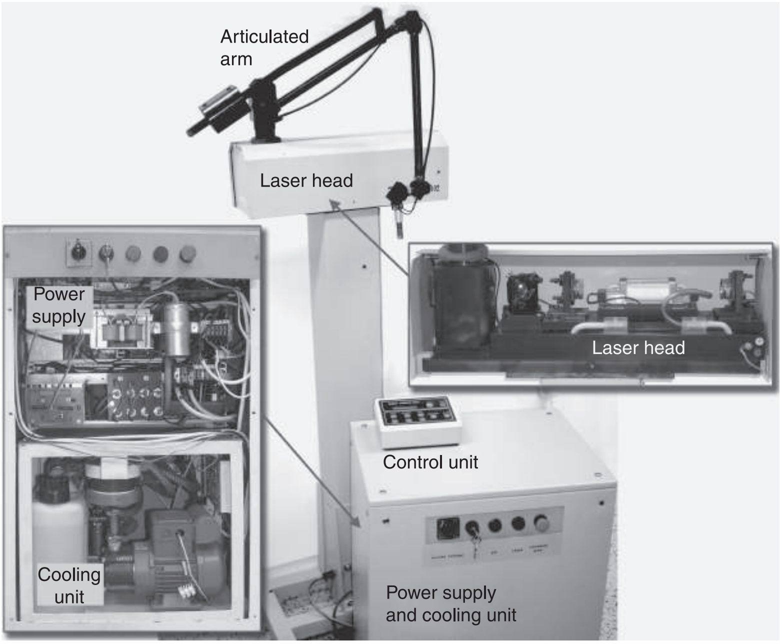
Nowadays many solid-state laser system types exist, from very small SSL microchips, through industrial and medical systems, up to huge thermonuclear fusion systems consisting of a laser oscillator and many laser amplifiers. Concerning the construction of these systems, also a variety of configurations exist depending on pumping (flashlamp-pumped, diode-pumped) and the active medium shape (rod, slab, thin disc, fiber). Nevertheless, the basic parts remain the same (see Section 2.2.1): laser head, pumping power supply, cooling, and laser control unit. Specific features of laser output characteristics directly depend on the properties of these components.

The simplest laser head consists of a laser active medium, a pumping source (flashlamp or laser diode), and an open resonator. Special optical components can be inserted into the resonator, affecting the operation of the laser (lenses, diaphragms, mechanical, optoelectronic or non-linear elements). The pumping power supply and cooling strongly depend on laser pumping radiation source and active medium configuration. The laser control unit is used to set and control laser beam parameters and simultaneously to monitor all laser subsystems to protect them against failure. As an example, the scheme of a medical solid-state laser system is shown in Fig. 5.2. In the previous section the laser active medium was described. The following two sections are devoted to pumping and cooling design.

5.3.1 Pumping of solid-state lasers

Flashlamp pumping

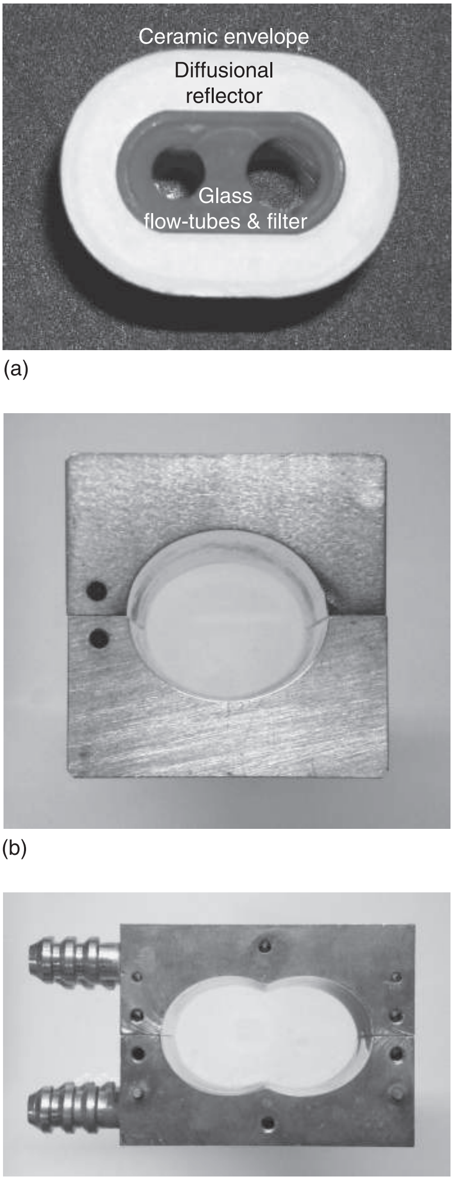
For optical excitation of active medium in a common solid-state laser, pulsed (xenon) or continuous (krypton or mercury) flashlamps are used. For maximum



5.2 Schematic of solid-state laser systems (dental laser driller).

utilization of the supplied energy, one or more flashlamps are placed parallel to the laser active medium in a specially shaped pumping cavity, which focuses the scattered light back into the active medium. During the 50 years of investigation of SSL many types of reflecting cavities were used – sphere, circular, elliptical, oval cylinder, etc. In Fig. 5.3 some of them are shown. Also, the inner reflected surface of the cavity is designed for the maximum reduction of pumping light reflection losses. The reflected area is silver or gold-plated, or the body of the cavity is produced from ceramic material with an extremely diffuse reflection. Today the most frequently used arrangement is the 'tight arrangement' in which the active medium and flashlamp are placed in parallel into the special reflected cylindrical ceramic cavity.

To ensure a sufficient electrical energy supply for a flashlamp-pumped laser head, whether continuous or pulsed pumping, is not a trivial problem due to a high excitation power, and its solution requires a special power supply source. Energy for pulse pumping is usually stored in a battery of capacitors (100–1000 μF) charged to the required voltage (500–5000 V). Special circuits control the shape and length of pumping pulse and discharge ignition (ignition voltage ranges in the tens of kV). Continuous lamps are powered from a stabilized current source (10–60 A, voltage 400–600 V). Operating pumping power is in hundreds of W/cm^2 of discharge surface and usually reaches several kW.



5.3 Types of laser reflecting cavities. Single-, double-oval cylindrical cavities (tight arrangement) (a); one-elliptical (b) and double-elliptical cylindrical cavities (c).

Due to the wide emission spectrum of flashlamps in comparison with the absorption bands of the laser active medium, and due to their spatial emission characteristics, the overall efficiency of the flashlamp-pumped laser does not exceed 1–2% (i.e. the conversion efficiency of electrical energy into laser beam energy), although the conversion efficiency of electrical energy into flashlamp light energy is very high (Xe-lamp: $\eta = 40$–70%). Unused energy is mostly converted into heat, which has to be extracted. This increases both the complexity and size of the laser system, and also the operating costs. Moreover, flashlamp operating time reaches hundreds of hours in the case of continuous operation and 10^6–10^7 pulses in pulsed operation (Koechner, 2006). In comparison with diode pumping, which will be explained in the following paragraph, the advantage of flashlamp pumping up to now is the higher output energy obtained.

Diode pumping

The breakthrough in the design of solid-state lasers came with optical pumping based on laser diodes (see Chapter 8). The advantage of a semiconductor laser is that it is a small laser with an active medium in the solid phase, which directly converts electrical energy into laser radiation energy suitable for solid-state laser pumping. The efficiency of energy conversion can reach up to 60%. The brightness of the laser diode is significantly higher in comparison with a flashlamp. Also, the emitted spectrum is much narrower and laser diode radiation can be effectively absorbed by the particular activator pumping transition.

The main factor leading to the rapid development of diode-pumped solid-state lasers is an effort to construct a reliable maintenance-free laser with high efficiency, easy and low cost operation. Compared with flashlamp pumping, diode lasers have the following advantages (Koechner, 1999):

- *Increasing of the laser system efficiency* Although the conversion efficiency of electrical energy to laser diode radiation reaches 20–60%, i.e. less than or comparable to that of lamps, it is possible by selective pumping of active ions to achieve overall efficiency of the diode-pumped laser from 10 to 20%.
- *Extended operation lifetime of pump system* Operating lifetime of the laser diode can be about 30 000 hours in continuous operation; in the pulse regime 10^9–10^{10} pulses can be generated.
- *Use of new laser materials* Because many of the active laser materials have very narrow absorption bands, or bands outside the spectral range of flashlamp emission, the use of selectively tuned laser diodes can be an efficient way of pumping.

- *Operating advantages* The smaller size of the resulting system, lower heat generation, less electrical noise, higher safety (operating voltage of flashlamps can vary from 100 to several thousand volts and currents from tens to thousands of amperes, while the operating voltage of laser diodes is in the range from 5 to 50 V at currents from units to hundreds of amperes), easy control of pulse shape and repetition rate, easy maintenance and replacement.

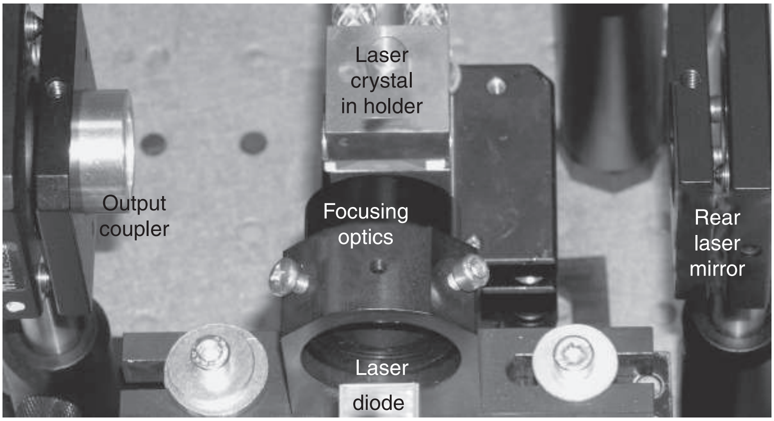
There are also some disadvantages of semiconductor lasers. Difficulties arise when high excitation energy of the pumping pulse is needed to reach or to operate at a non-standard emission wavelength or other parameters that go beyond the commercially available diodes. In contrast to flashlamps, laser diodes need special treatment because of the danger of static electricity damage.

A substantial drawback of currently available high-power laser diodes is, compared with other types of lasers, significantly worse quality of the generated laser beam (see Chapter 8). It is caused by the small dimensions of the semiconductor laser, by the asymmetric emitting area (the cross-section of the laser diode active area is in the order of $1 \times 100\,\mu m$) and a high gain, which supports generation of high-order transverse modes. Using special optics, which can significantly increase the laser diode price, the quality of the beam can be improved such that it is possible to guide the radiation into an optical fiber with relatively good efficiency (Botez and Scifres, 1994).

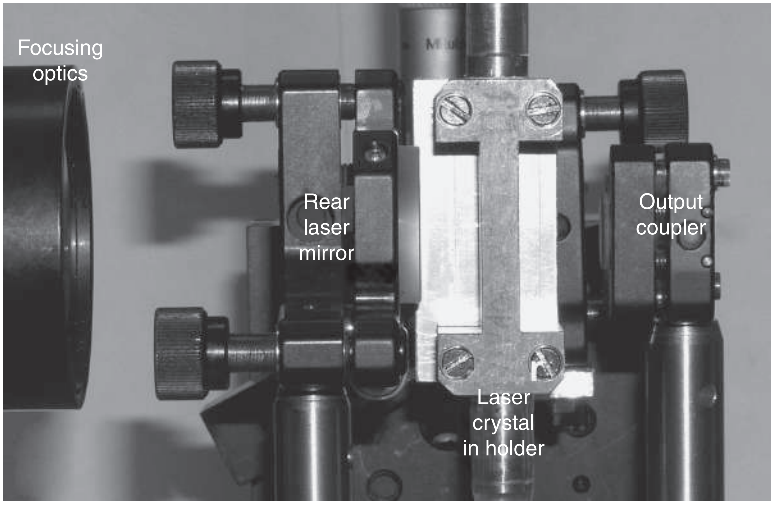
There are basically two main arrangements for solid-state active medium pumping using a laser diode – see Fig. 5.4. In the first case, the pumping radiation propagates perpendicularly to the direction of the generated laser beam. This method, known as transversal pumping, is used mainly for pumping of high power lasers. In the second option, referred to as longitudinal (axial) pumping, the pumping radiation propagates along the direction of the generated laser beam. In this case it is possible to ensure optimal overlap between pumping and the generated laser beam, allowing high conversion efficiency of the laser to be achieved. This pumping scheme is used in low and medium-power lasers (continuous pumping up to 250 W) (Koechner, 1999; Fan *et al.*, 1989; Shannon and Wallace, 1991).

5.3.2 Cooling of solid-state lasers

Mainly for flashlamp-pumped SSL, the laser active medium and pumping flashlamp have to be efficiently cooled. The transfer efficiency of the excitation energy into optical radiation is very low. A substantial part of the excitation energy is converted into heat in the active medium, and thus the conditions for laser action are changing. For a stable laser output (which is required mainly in



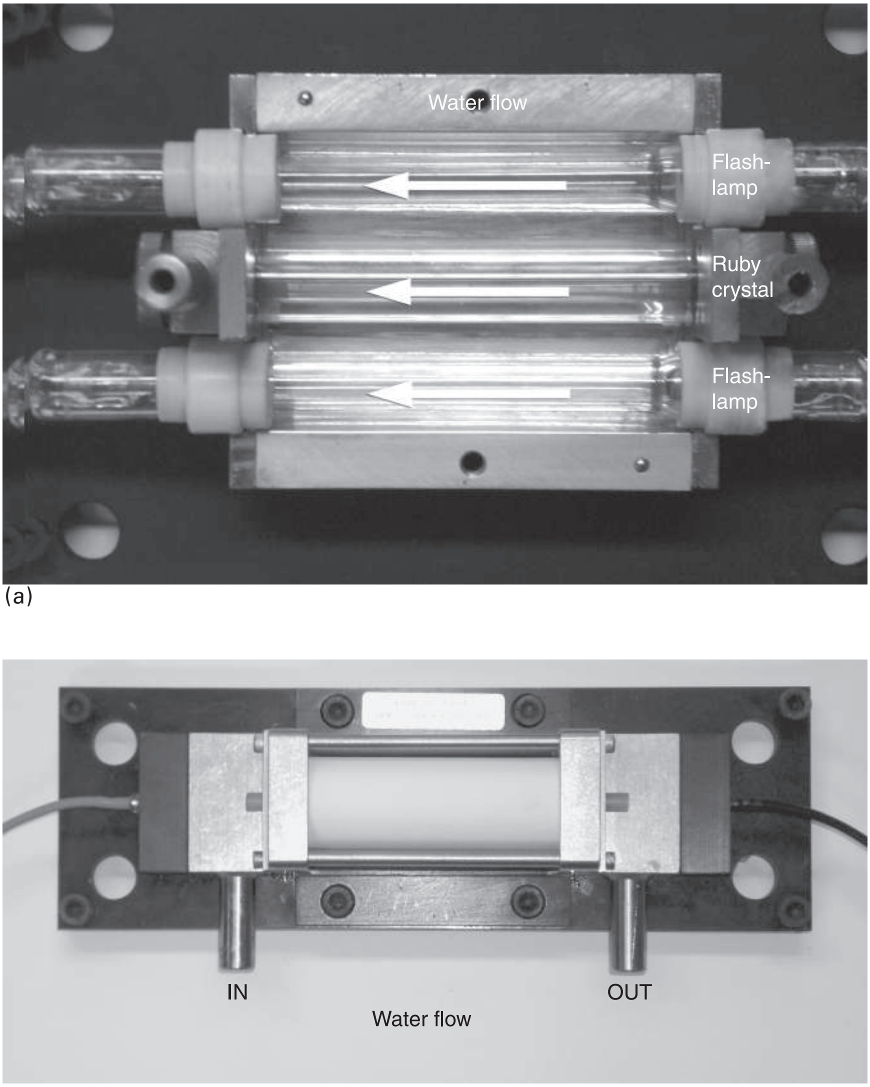
(a)



(b)

5.4 Photograph of the diode pumped solid-state laser: (a) transversal pumping, (b) longitudinal pumping.

medical instruments) it is necessary to maintain the active element and pumping source (flashlamp or laser diode) at a constant temperature. For this purpose a cooling system is used. For flashlamp-pumped lasers, the cooling inside the laser head is arranged so that flowing water fills the entire space of the reflected cavity. The other possibility is to place the active element and flashlamp into a tube through which cooling water flows – see Fig. 5.5. Outside the laser head is a



(a)

(b)

5.5 Cooling of flashlamp pumped solid-state laser: (a) water flow along ruby crystal and flashlamps placed inside glass tubes in double elliptical cavity, (b) water input and output to ceramic cavity (water is inside whole cavity where crystal and flashlamp are placed).

thermostat (see Fig. 5.2) to ensure a constant temperature of the cooling fluid in the range of ±1°C. For small, low-power lasers (typically diode-pumped) air cooling, alone or in combination with thermoelectric cooling with a Peltier element, is used.

5.3.3 Modes of operation

Properties of solid-state active medium (e.g. long lifetime, high energy storage, high damage threshold) allow laser operation in many regimes. The particular operation mode is given by the pumping regime and can be affected by the use of special optical elements placed in the resonator (Siegman, 1986; Svelto, 1998; Koechner, 1999):

- *Continuous generation.* The laser active medium is pumped continuously, the population of energy levels of the active medium is stationary, the generated laser radiation power is stable – continuous wave or continuous waveform (CW) (see Fig. 2.16(a)).
- *Quasi-continuous generation.* Pulse pumping of laser active medium is used. The pump pulse is much longer than the duration of transient effects which appear after the moment when the laser starts to be generated. After this time the laser performance can be considered as stable – quasi-continuous waveform (QCW) (see Fig. 2.17(a)).
- *Free-running.* Pulse pumping of laser active medium is used. The pump pulse is long enough to reach stable conditions for generation; intensity of output radiation has an irregular, random timing and amplitudes – spiking (Fig. 2.16(b)).
- *Q-switching.* Pulsed and/or continuous pumping is possible. A special optical element (so called Q-switch) is used to control the cavity losses – resonator quality Q. The energy, accumulated in the laser active medium at the time when the resonator quality Q is artificially reduced by the Q-switch, is released in one short, high-energy, high-power pulse (giant pulse; Fig. 2.17(b)) after a sudden increase in resonator quality. The pulse length depends on the amount of stored energy and the resonator parameters.
- *Gain switching.* Pulsed pumping is used. The pumping pulse duration is much shorter than the lifetime of the upper laser level. Thanks to the intense pumping, the high gain is achieved in a short period in the active medium, which leads to a giant pulse generation, similarly to the Q-switching regime. The pulse length depends on the amount of energy pumped and resonator parameters.
- *Cavity dumping.* Pulsed and/or continuous pumping is possible. Both laser resonator end mirrors have 100% reflectivity. The energy accumulated in the electromagnetic field inside the resonator is emitted after a sudden replacement of one mirror (this can be realized by an element similar to that used for Q-switching). The pulse length is determined by the laser resonator round-trip time.
- *Mode-locking.* Pulsed and/or continuous pumping is possible. By modulation of some resonator parameter (losses, phase delay) with the period corresponding to the resonator round-trip time, it is possible to reach the synchronization of longitudinal cavity modes, which leads to generation of a pulse train. The

length of individual pulses is much shorter than the optical cavity round-trip time, in the range of 10^{-10}–10^{-15} s. This length depends on the active material spectral gain width and the parameters and arrangement of the optical resonator and all optical elements inside it (see Fig. 2.18(a,b)).

Long pulse and continuous operation

The simplest mode of laser operation is called a *free-running* regime. In this case the laser cavity consists only of the laser resonator and active medium pumped above the laser generation threshold level. Excitation power can be supplied continuously or in pulse, while the duration of these pulses is comparable to that of active medium upper laser level lifetime and the increase in population inversion levels is slow compared with the resonator round-trip time.

In a short time (comparable to the upper laser level lifetime), after the beginning of the pumping the laser starts to generate in a transient regime which continues until stabilization of the balance between energy pumped and emitted. In this period the laser generates a random sequence of light pulses whose amplitude, duration, and peak position depend on many external factors affecting the pumping speed and the threshold condition for various modes of laser resonator. Laser radiation for this period behaves very freely, and irregular relaxation oscillations are called spikes. After some time from the start of pumping to establish a certain constant level of intensity of laser light, continuous mode can be reached if the pumping lasts a sufficiently long time – see Fig. 2.16(a).

Nanosecond pulse operation

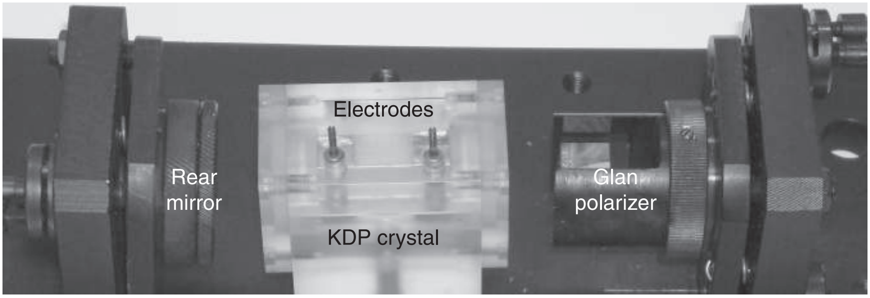
A method most often used for generation of nanosecond, high peak power, laser pulses is called Q-switching. With this method it is possible to generate pulses with duration ranging from fractions to hundreds of nanoseconds with peak power from 10 kW to 100 MW – so-called *giant pulses*. The principal mechanism of short, high-energy, Q-switched pulse generation is a fast release of energy, accumulated in the laser active medium. Resonator losses are artificially increased at the beginning of laser pumping – one resonator mirror is readjusted or covered by a Q-switch element (the value of the resonator quality factor Q is very small), which prevents the formation of relaxation oscillations and laser generation because photons cannot come back through the active material, positive feedback is interrupted and the laser threshold is thus increased. If the upper laser level lifetime is long enough, it is possible to increase the population inversion, the gain, and the energy accumulated in the active medium to very high values which are not available in the regime of free-running generation. At the appropriate moment (when the maximum possible inversion is reached) the resonator losses are quickly reduced to the normal value (quality factor increases, the threshold for generation decreases). At this time an exponential increase of the laser radiation intensity begins inside the resonator and the avalanche growth in the number of photons leads to the build-up of the giant pulse.

The duration of the generated pulse is generally much shorter than the time required to achieve population inversion. The energy stored in the active medium during a relatively long period of excitation is dissipated within a very short interval (0.1–100 ns). The peak power of Q-switched pulse can be up to six orders of magnitude greater than intensities achieved in continuous mode at the same pumping level.

The Q-switched mode of operation is implemented in practice by inserting a special optical shutter called a Q-switch inside the laser resonator. This element ensures the appropriate modulation of the resonator losses. The basic requirement for this element is to change its losses during a time comparable with the pulse build-up time. There are currently four types of Q-switches, differing in the phenomenon used for modulation of losses: a passive saturable absorber, using the non-linear absorption of certain solid or liquid substances; active electro-optical (see Fig. 5.6); acousto-optical; and a mechanical shutter (Koechner, 2006).

Generation of ultrashort pulses

This section is devoted to the mode-locking method of generation of short pulses by synchronizing the laser longitudinal modes. By this method the pulses with duration of picoseconds (10^{-12} s) and, for special materials and conditions, femtoseconds (10^{-15} s) can be generated. The principle of formation of such short pulses is a superposition – a constructive interference of phase synchronized longitudinal resonator modes. Mode-locking is a binding–correlating of axial modes (spectral amplitudes and phases) within the laser resonator. It is a resonance phenomenon based on a relatively weak synchronous modulation (synchronous with the circulation of radiation inside the resonator) which causes the generation



5.6 Photograph of the electro-optical Q-switch – Pockels cell – operated at a quarter-wave retardation voltage.

of a pulse shorter than the period of circulation (less than a round-trip $2L/v$, where L is the length of the resonator, v the velocity of propagation of radiation in the resonator).

In a free-running laser, transverse as well as longitudinal modes oscillate simultaneously inside the resonator without fixed mode-to-mode amplitude and phase relationships. The resulting laser output is a time-averaged statistical mean value. In the frequency domain, the radiation consists of a large number of discrete spectral lines. Each mode oscillates independently of the others. The phases are randomly distributed in the range $-\pi$ to $+\pi$. In the time domain, the field consists of an intensity distribution which has the characteristics of random noise (Fig. 2.16(b)).

For the mode-locking regime the generation in a single transverse mode (TEM_{00}) must be ensured. Then some element (mode-locker) should be inserted inside the resonator which ensures that the oscillating longitudinal modes are forced to maintain a fixed-phase relationship to each other. Then the output as a function of time will be varied (ideally) in a well-defined manner. In the output the spectral intensities have a Gaussian distribution and spectral phases are zero. In the time domain the radiation inside the resonator is a short single Gaussian pulse. The length of the generated pulses is inversely proportional to the number of longitudinal modes (N) which can be synchronized. The number of modes in the resonator depends generally on the bandwidth of the active medium gain, so with increased bandwidth of the active material ($\Delta\nu$) pulses with shorter length (Δt) can be generated (Table 5.3).

Synchronization modes can be achieved by various methods generally based on periodic changes of laser parameters (gain, internal losses, length of the resonator, etc.). The period of these changes must be equal to the time of photon circulation inside the resonator. If periodic parameter changes are caused by external effects, the method is called active synchronization, active mode-locking. If the laser internal parameters are caused by a non-linear change of an element inside the resonator, it is called passive synchronization, passive mode-locking. A detailed description of these methods can be found in many books (e.g. Svelto, 1998; Siegman, 1986; Koechner, 1999; Saleh and Teich, 1991).

Table 5.3 Examples of lasers generating short (mode-locked) pulses

Laser medium	λ	$\Delta\nu$	Δt
Ti:sapphire	850 nm	100 THz	4.4 fs
Cr:LiSAF	850 nm	57 THz	8 fs
Rhodamin 6G	570 nm	45 THz	10 fs
Nd:glass	1054 nm	8 THz	55 fs
Nd:YLF	1047 nm	390 GHz	1.1 ps
Nd:YVO_4	1064 nm	338 GHz	1.3 ps
Nd:YAG	1064 nm	135 GHz	3.3 ps

Table 5.3 shows the length of pulses that can be reached for various active media. In contrast to the Q-switching method, which is used mainly for solid-state lasers, in mode-locking regime the solid-state, dye, gas, and semiconductor lasers can work. Most known systems generating short pulses (10 fs) are Ti:sapphire, Cr:LiSAF and Rhodamine 6G (Table 5.3).

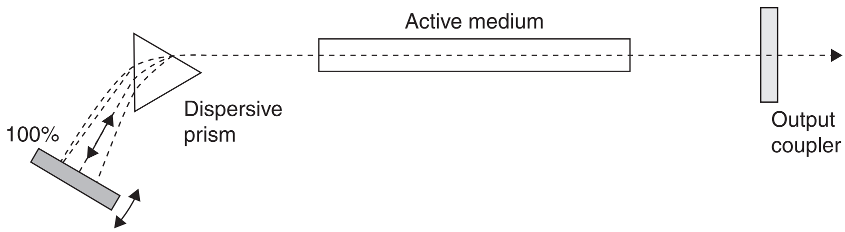
5.3.4 Tunable solid-state lasers

Up to now we have described only lasers which generate one (or in special cases two or more) discrete wavelengths. The broad emission spectrum of some laser active media allows the construction of lasers whose emission wavelength can be continuously changed (tuned). Some examples of tunable lasers are given in Table 5.4. Such lasers are used in applications where specific wavelength and change of the wavelength during treatment are needed. The specific wavelength corresponds to resonator minimum losses at maximum gain of active medium. Resonators whose losses are strongly wavelength-dependent are called dispersive or wavelength-selective. This wavelength dependence of losses is achieved by placing one or more dispersive elements inside the non-selective resonator (Mollenauer and White, 1987; Durante, 1995).

The dispersive elements typically use standard physical principles such as the dispersion of the refractive index, birefringence of crystals, gratings diffraction, interference, and so on. A simple optical element enabling broadband tuning of the laser emission is a dispersive prism placed inside the laser resonator. The basic layout of the resonator with a dispersive prism is shown in Fig. 5.7. The laser beam passes through the prism symmetrically and the refractive angle is chosen so that the beams hit the prism at the Brewster angle, minimizing the losses of this element. The light rays after passing the prism are spread angularly in beams with different frequencies. Only beams perpendicular to the

Table 5.4 Tunable solid-state lasers

Laser type	Chemical formula	Tuning wavelength [μm]
Alexandrite	$Cr:BeAl_2O_3$	0.71–0.82
Titan sapphire	$Ti:Al_2O_3$	0.66–1.1
LiSAF	$Cr:LiSrAlF_6$	0.75–1.0
LiCAF	$Cr:LiCaAlF_6$	0.7–0.9
Nd:LMA	$Nd:LaMgAl_{11}O_{19}$	1.05–1.06; 1.075–1.085
Cr:YAG	$Cr:Y_3Al_5O_{12}$	1.32–1.53
Cr:Fosterite	$Cr:MgSiO_4$	1.13–1.345
Tm:YAP	$Tm:YAlO_3$	1.85–2.03
Ho:YAG	$Ho:Y_3Al_5O_{12}$	2.07–2.13
Cr:ZnSe	Cr:ZnSe	2.0–3.1
Fe:ZnSe	Fe:ZnSe	4–4.5



5.7 The scheme of laser resonator tuned using a dispersive prism.

rear mirror are reflected back through the prism and are amplified in the active medium. Turning this mirror or prism allows the laser operation wavelength to be selected.

The *dispersive prism* is one of the less selective elements, which may be advantageous for some applications (e.g. a tunable laser operating in a mode-locking regime). The main advantages of using a dispersive prism are a wide range of working wavelengths (limited range of frequency agility gain active medium and the transmission curves used mirrors), the low insertion losses for horizontally polarized light (p-polarization, the TM-polarization) and a high threshold for optical damage.

A frequently used tuning element is a birefringent plate, called a *Lyot filter*. It consists of one or more plates of a birefringent material (e.g. Y-cut of monocrystalline quartz) placed between two correspondingly oriented polarizers. Only the wavelengths for which the birefringent filter turns the plane of polarization about π are transmitted without losses. The wavelength is tuned by rotating the filter around the normal to the surface plane. Because the plates are inserted into the resonator under the Brewster angle relative to axis of the resonator, the insertion losses of the filter are very small. The optical damage threshold of the filter is very high. The spectral width of the main peak throughput birefringent filter is approximately 1 nm.

For the generation of very narrow lines, a *diffraction grating* can be used as a tuning element. There are a large number of possible resonator arrangements, but in principle it can be used like a dispersion prism, such as bending in combination with a tuning mirror, or directly as a frequency selective mirror closely. The main disadvantage of these dispersed elements is a low threshold of optical damage.

If the application requires radiation with a narrower spectral line than that offered by the above methods, it is possible to insert into the resonator one or more etalons. The etalon is based on the principle of constructive interference. In the simplest case it consists of two partially reflecting surfaces, forming a Fabry-Perot etalon, which is used as a tunable narrowband optical filter.

5.3.5 Solid-state lasers with non-linear conversion

As is seen from the above description, lasers can generate many laser wavelengths. The non-linear optics gives the possibility of obtaining new frequencies: when intensive laser radiation propagates through a non-linear environment, radiation with a new wavelength can be generated. Phenomena that may occur are the generation of sum and difference frequencies (the most used is the second harmonic frequency generation), Raman or Brilouin scattering, or parametric generation (for a summary of the non-linear effects, see Table 5.5) (Koechner, 1999; Boyd, 2008). This technique extends the frequency range of available sources of laser radiation. In 1961, Franken and colleagues detected ultraviolet radiation corresponding to twice the frequency of the ruby laser after the laser beam passed through the crystal of quartz (Franken *et al.*, 1961). This experiment is considered to be the beginning of intensive research and the use of non-linear material properties.

Table 5.5 Non-linear effects used for laser frequency conversion

Non-linear process description	Generated frequency	Used non-linear materials	Application example
Harmonic generation – radiation with frequency ω is converted to new radiation with *n*-times higher frequency (*n* is odd integer). Conversion efficiency decreases with increasing *n*.	$2\omega, 4\omega, \dots, n\omega$	Birefringent crystals $KTiOPO_4$ (KTP), LiB_3O_5 (LBO), β-BaB_2O_4 (BBO), $LiNbO_3$, periodically pooled $LiNbO_3$ (PPLN)	KTP-laser uses conversion of infrared 1064 nm laser radiation using second harmonic generation (SHG) in KTP crystal. Green radiation at 532 nm is obtained.
Sum frequency generation – radiation with frequency ω_1 and ω_2 is mixed and converted to new radiation with frequency corresponding to sum of both frequencies $\omega_1 + \omega_2$.	$\omega_1 + \omega_2$	Birefringent crystals used for harmonic generation	Third harmonic generation (THG, 355 nm) from Nd:YAG laser is generated as a sum frequency of first (1064 nm) and second harmonic (532 nm) radiation.
Difference frequency generation – radiation with frequency ω_1 and ω_2 is mixed and converted to new radiation with frequency corresponding to difference of both frequencies $\omega_1 - \omega_2$.	$\omega_1 - \omega_2$	Lo-OH birefringent crystals	

Table 5.5 Continued

Non-linear process description	Generated frequency	Used non-linear materials	Application example
Optical parametric generation – signal radiation with frequency ω_s and pump radiation with frequency ω_p are mixed in non-linear crystal. The signal radiation is strongly amplified (broadband noise is possible to amplify) and idler radiation is generated ($\omega_i = \omega_p - \omega_s$). For fixed pump frequency the output signal and idler are tunable.	Broadband range of ω_s and ω_i, depending on used crystal and geometry $\omega_s + \omega_i = \omega_p$, $\omega_i < \omega_s < \omega_p$	Birefringent crystals used for harmonic generation	Optical oscillator based on parametric generation (OPO – optical parametrical oscillator), pumped by second harmonic radiation of Nd:YAG laser at 532 nm, can cover spectral range from 680 up to 2400 nm.
Stimulated Raman scattering (SRS) – radiation with frequency ω is converted to new radiation with frequency shifted about fixed value Ω (or its integer multiple) to lower (Stokes shift) or to higher (Anti-Stokes shift) frequencies. Frequency shift Ω is done by used material.	n^{th} Stokes frequency $\omega - n\Omega$, n^{th} Anti-Stokes frequency $\omega + n\Omega$	Gases (H_2 $\Omega = 12.5$ GHz, CH_4 $\Omega = 8.74$ GHz, N_2 $\Omega = 6.99$ GHz), solids ($BaWO_4$ $\Omega = 2.78$ GHz, $Ba(NO_3)_2$ $\Omega = 3.14$ GHz)	Yellow radiation (563 nm) generation from Nd:YAG laser SHG (532 nm) using SRS at $Ba(NO_3)_2$. Eye-safe radiation generation (1542 nm) from Nd:YAG laser (1064 nm) using SRS at CH_4 gas cell.

Harmonic generation

Harmonic generation is a non-linear optical process in which photons of intense incoming laser radiation interact with a non-linear material and radiation with corresponding harmonics frequencies is generated. This typically occurs at optical intensities of the order of 10^{14} W/cm^2 or higher. This procedure is often used in laser physics for obtaining a new shorter wavelength from the basic laser radiation. The second harmonic radiation (SHG) is most often used in the application (see KTP laser). In this non-linear optical process, photons which interact with a non-linear material are effectively ‘combined’ to form new photons with twice the energy, and therefore twice the frequency and half the wavelength of the initial photons. It is a special case of sum frequency generation.

Parametric generation

The optical parametric generation process uses a second-order non-linearity, which leads to the interaction of three optical fields. In the practical implementation, the parametric process is initiated by an intense pumping beam at frequency ω_p entering the non-linear crystal. This field, whose source is usually a laser, through the non-linear susceptibility is mixed with the signal field with frequency ω_S, thus producing an idler wave at the frequency $\omega_i = \omega_p - \omega_s$. Under the conditions implied by the law of conservation of energy and the momentum of photons participating in the parametric generation (so-called phase synchronism), this process can continue until the strong pumping beam is transformed into the signal wave, which is weak at the beginning and can grow to macroscopic levels thanks to parametric amplification of signal wave (Armstrong *et al.*, 1962; Boyd, 2008).

The optical parametric oscillator (OPO) is a radiation source based on non-linear optical parametric amplifier gain. Although parametric oscillators have similar properties to lasers, in some important aspects they are different (Saleh and Teich, 1991; Koechner, 1999). For example, while the laser can be pumped by incoherent sources, OPO requires a high degree of coherence excitation. In the non-linear crystal, there is no accumulation of energy and the amplification occurs only for the period during which the pumping radiation is present. An important feature of parametric generators is a broad tunability based on angularly sensitive birefringence of anisotropic crystals, or on temperature dependence of the refractive index (Butterworth *et al.*, 1996; Ruffing *et al.*, 2001; Bode *et al.*, 1998). For a single Nd:YAG pump source operating at 1064 nm in combination with SHG and third harmonic generation (TGH), a wavelength range from 250 to 2100 nm can be covered.

Raman frequency conversion

The stimulated Raman scattering (SRS) process occurs when the light intensity inside the Raman non-linear medium reaches a certain (threshold) level. The incoming pump light induces intense molecular or lattice vibrations and these modulate the incoming light beam, generating frequency-shifted radiation. The interaction of the intense electrical field with Raman material causes the output radiation shift toward a longer wavelength (first Stokes shift). For sufficiently high applied pump intensities, other additional lines at longer, as well as shorter, wavelengths with respect to the pump wavelength will be generated (anti-Stokes and higher Stokes lines). The spectral areas reachable with SRS extend from ultraviolet to mid-infrared, depending on the pump laser and Raman material used (Boyd, 2008).

The spontaneous generation of new frequencies in Raman media has been known since Raman and Krishnan, as well as Mandelstam and Brillouin, discovered it in 1928. SRS was first observed in 1962 by Woodbury and Nag (Woodbury and Nag, 1962) while studying ruby laser Q-switching with a nitrobenzene cell. Efficient SRS has been experimentally realized in liquids, gases, and solid-state materials (Eckhardt, 1966; Hanna *et al.*, 1986). New wavelengths found many practical applications in spectroscopic analysis of substances, pollution measurement, biomedical diagnostics or medicine. However, for practical applications mainly cells filled with gases such as methane, hydrogen, and nitrogen were used for a long time. Today, solid-state materials such as $Ba(NO_3)_2$, $KGd(WO_4)_2$, $BaWO_4$, or synthetic diamond, possessing favourable features for stimulated Raman scattering, are used because these devices have shown efficient and reliable performance (Basiev *et al.*, 1999; Hulliger *et al.*, 2001; Cerny *et al.*, 2004; Basiev *et al.*, 2005; Pask *et al.*, 2008; Mildren *et al.*, 2008). Their compactness and robustness in comparison with large high-pressure-gas-filled cells make them promising candidates for use in all-solid-state laser systems. A new development is the combination of active and non-linear laser materials (non-linear crystal doped by active ion) directly generating Raman radiation. In this context the crystals Nd:KGW, Nd:$SrWO_4$, or Nd:$PbMoO_4$ may be mentioned (Andryunas *et al.*, 1985; Kaminskii *et al.*, 2001; Voronina *et al.*, 2003; Brenier *et al.*, 2004; Jelínková *et al.*, 2004).

5.4 Solid-state lasers for medical applications

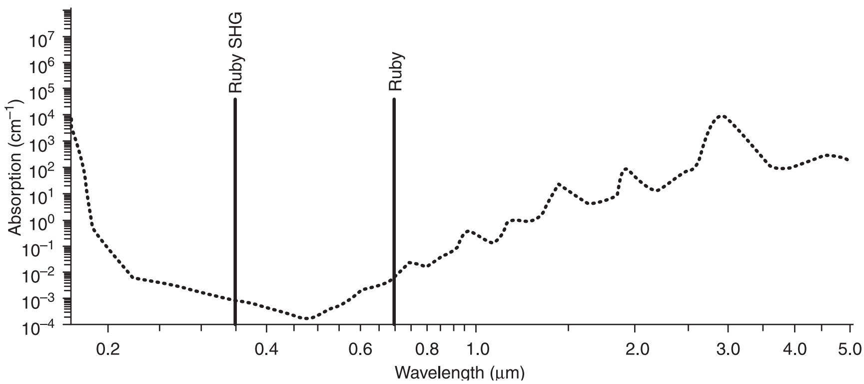
In this section some of the solid-state lasers often used in medicine are described, together with the new laser systems which have been investigated in recent years and may potentially be used for medical diagnostics or treatment. Taking into consideration that water is one of the major tissue components and that radiation absorption by it is one of the defining conditions of interaction (see Chapter 1), the descriptions of all lasers in this chapter are supplemented by a graph of absorption of laser radiation in water.

5.4.1 Ruby laser

The ruby laser was the first with which laser radiation was generated (Maiman, 1960). Ruby was also the first laser used in medical applications. It is not so obviously used today, but it is mentioned here primarily from a historical point of view. The active material of the ruby laser is a monocrystal of synthetically grown sapphire (Al_2O_3) (matrix) in which a small percentage of Al^{3+} ions are replaced by chromium Cr^{3+} transition-metal ions. Due to the sapphire matrix, a ruby crystal has good physical and chemical properties: excellent hardness and durability, good thermal conductivity and chemical stability. It has been grown in very high quality by the Czochralski method. At room temperature the ruby can work in a pulsed regime – free-running, Q-switched, and exceptionally in mode-locking regime. The main characteristics of the ruby crystal and ruby laser are summarized in Table 5.6. From the viewpoint of application in medicine, the ruby red and blue (SHG) radiation has low absorption in water (Fig. 5.8) and therefore penetrates

Table 5.6 Ruby lasers characteristics

Material	Ruby crystal		
Matrix	Sapphire – Al_2O_3		
Active ions	Cr^{3+}		
Wavelength fundamental	694.3 nm		
SHG wavelength	347.1 nm		
Photon energy	2.86×10^{-19} J, 1.79 eV		
Level scheme	3		
Lifetime of upper laser level	3 ms (at room temperature)		
Main pumping bands	Blue 404 nm, green 554 nm		
Pumping	Flashlamp only		
Cooling system	Water		
Operation mode	Free-running	Q-switched	Mode-locked
Pulse length	1 ms	10–30 ns	10 ps
Generated energy	~ 5 J	< 1 J	10 mJ
Medical applications	Dermatology, ophthalmology (in the past)		



5.8 Ruby laser emission on the basis of the absorption of radiation in water.

into the water contained in tissue. After the first boom of its use in ophthalmology and dermatology, nowadays the ruby laser is used in dermatology only (removing tattoos, pigmented spots, etc.).

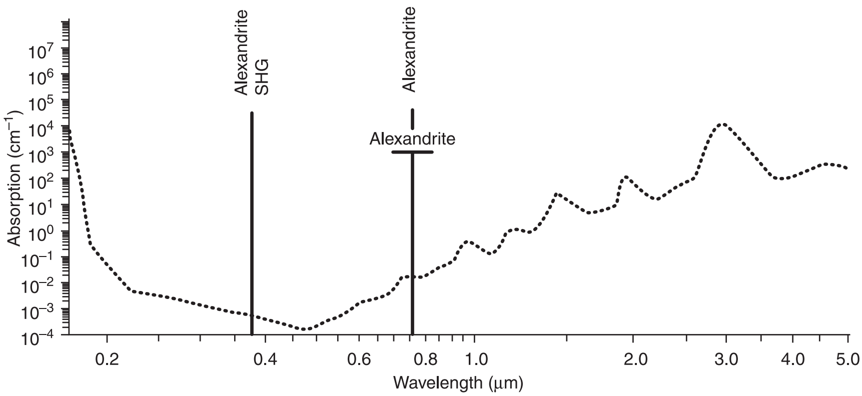
5.4.2 Alexandrite laser

The alexandrite–chromium doped chrysoberyl (Cr^{3+}:BeO.Al_2O_3) laser is a broadly tunable solid-state vibronic system that operates at wavelengths between 700 and 800 nm. The growth of alexandrite crystals for laser application was begun in the early 1970s, and in 1974 the first alexandrite laser (working in a three-level scheme, as ruby) was put into operation (Morris and Cline, 1976). Since 1977, when its tunability was discovered (four-level scheme) (Walling *et al.*, 1985), significant progress has been made in alexandrite's crystal growth, and its other laser properties have been intensively investigated (Morris and Cline, 1976; Cline *et al.*, 1979; Walling *et al.*, 1980). Due to beryllium being extremely poisonous, alexandrite crystals are produced by a limited number of companies (Allied Corp.) and their price is obviously very high. Their particularly significant properties include the fact that alexandrite lasers do not only operate well at room temperature, but, due to unusual excited state properties, their performance actually improves at elevated temperature. Alexandrite lasers have been operated in most of the basic configurations used in solid-state laser technology, including pulsed and CW, Q-switched, and mode-locked regimes. The fundamental output of alexandrite, nominally 755 nm, is valuable for spectroscopic studies. More interesting for photochemical applications is the frequency doubled band (SHG) from 360 to 400 nm, where many photochemical reactions are realized. Due to Raman shift, it is possible to reach other wavelengths in the IR region. With the help of non-linear optical technique, it is possible to cover the wavelength region from 170 nm to 18 μm. The pumping of alexandrite lasers is performed by flashlamp as well as coherently by argon (see Chapter 6) or semiconductor laser (Chapter 8). The alexandrite laser itself can be used for coherent pumping of other laser materials such as Nd:YAG, Cr:forsterite, and others. The main characteristics of alexandrite crystal and laser are summarized in Table 5.7.

Regarding medical applications, the alexandrite laser can be comparatively quick to use due to larger spot sizes delivered through fiber optic systems (Chapter 4). Due to low absorption in water (see Fig. 5.9), the wavelength of 755 nm penetrates more deeply into the skin, and it is commonly used in

Table 5.7 Alexandrite lasers characteristics

Material	Alexandrite		
Matrix	$BeO.Al_2O_3$		
Active ions	Cr^{3+}		
Wavelength – tunable	710–820 nm		
SHG wavelength	375 nm		
Photon energy	2.65×10^{-19} J, 1.65 eV		
Fluorescence lifetime	260 μs (at room temperature)		
Main pumping bands	Blue 400 nm, green 550 nm		
Operation mode	CW	Free-running	Q-switched
Pump mechanism	Flashlamp	Flashlamp	Flashlamp
Length of pulse		200 μs–10 ms	20 ns
Generated energy/power	100 W	Tens of J	Units of J
Repetition rate		1 Hz–100 kHz	< 50 kHz
Cooling system	Water	Water	Water
Medical applications	Dermatology, urology, dentistry		



5.9 Alexandrite laser emission on the basis of the absorption of radiation in water.

dermatology for hair removal and tissue rejuvenation. It is also used instead of the ruby laser for removing nevi and tattoos, either artificial or resulting from accidents (Chapter 14). Another application is breaking stones in urology (Chapter 16). The alexandrite laser is less likely to damage the ureter wall, as it will not melt the wires of a basket or guidewire.

5.4.3 Ti:Sapphire laser

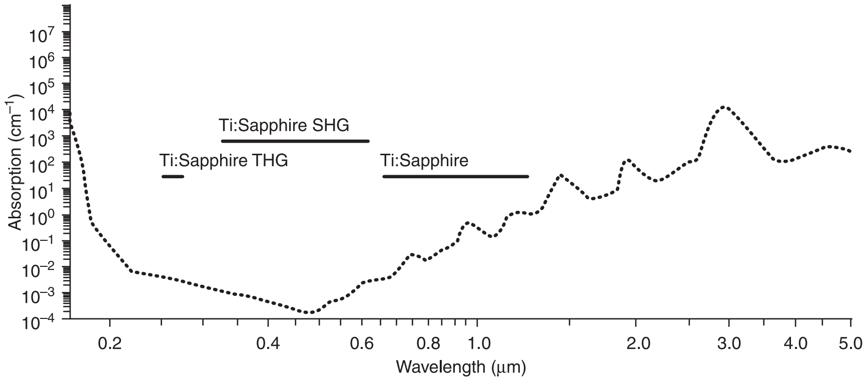
The Ti:sapphire laser (Ti:Al_2O_3) is a tunable laser which emits red and near-infrared light in the range from 650 to 1180 nm. Twenty-two years after the ruby laser was discovered, P. E. Moulton demonstrated the generation of a Ti:sapphire laser in which the Cr ion in the Al_2O_3 matrix was substituted by titanium transition-metal ion (Moulton, 1986). Its main characteristics are summarized in Table 5.8. Also, like ruby, the Ti:sapphire (due to the sapphire matrix) has an excellent thermal conductivity, alleviating thermal effects even for high laser powers and intensities.

The upper-state lifetime of Ti:sapphire is very short (3.2 μs). This makes optical non-coherent flashlamp pumping of this material difficult. Nevertheless, during the first experiment xenon flashlamps were used for reaching the population inversion in Ti:sapphire. Due to the requirement for short generated flashlamp length (around units of μs), the lifetime of the flashlamp was very short. Therefore the main source for pumping of this laser nowadays is coherent radiation, mainly from the green spectral region. Due to the very high saturation power of Ti:sapphire, the pump intensity needs to be high, so that a strongly focused pump beam and thus a pump source with high beam quality is required. In most cases, a pump power of several units to tens of watts is used. Initially, coherent pumping

Table 5.8 Ti:Sapphire laser characteristics

Material	Ti:Al_2O_3 crystal			
Matrix	Al_2O_3			
Active ions	Ti^{3+}			
Wavelengths	650 nm to 1180 nm			
SHG wavelengths	325 nm to 590 nm			
THG wavelengths	252 nm to 267 nm			
Level scheme	4			
Photon energy for 800 nm	2.48×10^{-19} J, 1.55 eV			
Lifetime of upper laser level	3.2 μs (at RT)			
Main pumping bands	510–530 nm			
Operation mode	CW	Free-running	Q-switched	Mode-locked
Pump mechanism	Argon laser, SHG Nd lasers, flashlamp, diode laser			
Length of pulse		10 μs	2–100 ns	5 fs–50 ps
Average output power	< 50 W		1–2 W	1 W
Output pulsed energy		5 J	1 J	10–100 nJ
Repetition rate		1 Hz–100 kHz	1–40 Hz	10–100 MHz
Cooling system	Water, Peltier cooler			
Medical applications	Ophthalmology, dentistry			

of the Ti:sapphire laser was performed by an argon ion laser with 514 nm wavelength. Due to high inefficiency and cost, the argon laser was replaced by frequency-doubled solid-state lasers based on neodymium-doped gain media (Nd:YAG, Nd:YLF, or Nd:YVO_4), generating radiation with the wavelengths 527–532 nm. Also, diode pumping is starting to be used. Ti:sapphire lasers operate most efficiently at wavelengths near 800 nm. They can work in a pulsed as well as a continuous regime. With an appropriate design, Ti:sapphire lasers can operate in continuous wave regimes with extremely narrow line widths tunable over a wide range. Due to the wide spectrum of frequency components, the exceptional usage of Ti:sapphire lasers is for the generation of ultrashort pulses. This is due to the inverse relationship between the frequency bandwidth of a pulse and its time duration. Ultrashort pulses with a typical duration between 10 fs (in special cases even around 5 fs) and a few picoseconds can be generated. The pulse repetition frequency is in most cases around 70 to 90 MHz. Such an oscillator has an average output power of 0.5 to 1.5 W. Ti:sapphire lasers are now commercially available and are a valuable research tool found in many laboratories. They are also very convenient for pumping test setups of new solid-state lasers (e.g. based on neodymium- or ytterbium-doped gain media), since they can easily be tuned to the required pump wavelength and allow one to work with very high pump brightness due to their good beam quality and high output power of typically several watts. As regards medical applications (Ti:sapphire laser radiation absorption in water; see Fig. 5.10), the main use is in ophthalmology for keratectomy treatment (see Chapter 13).



5.10 Ti:Sapphire emission on the basis of the absorption of radiation in water.

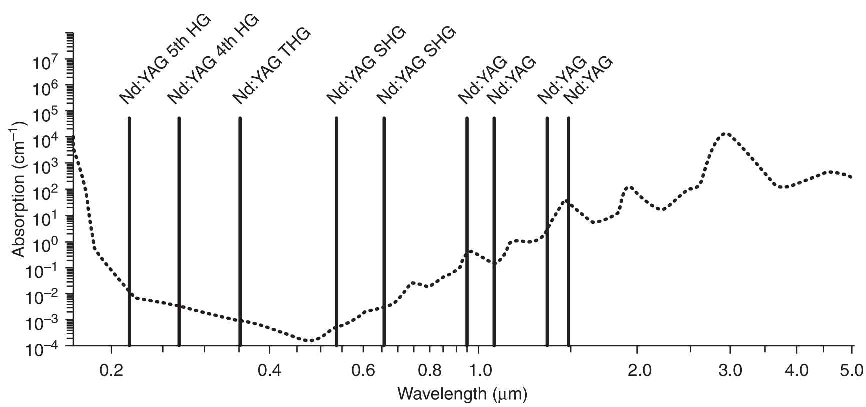
5.4.4 Nd-doped lasers

Trivalent neodymium ion Nd^{3+} was the first lanthanide from rare-earth elements used for the generation of laser radiation. The Nd:$CaWO_4$ laser was developed in 1961 (Johnson and Nassau, 1961). Historically, it was the third laser which was put into operation (the first was ruby, the second the U^{3+}:CaF laser). Over the years the neodymium laser became one of the most used lasers for application purposes. The success of the Nd^{3+} ion lies in the structure of its energy levels and in the spectroscopic properties suitable for the generation of laser radiation. In 1964 Geusic *et al.* (Geusic *et al.*, 1964) demonstrated the operation of neodymium ion in YAG matrix $Y_3Al_5O_{12}$. It is a four-level laser with lower threshold and with excellent mechanical and temperature properties. For optical pumping of this material it is possible to use non-coherent flashlamp radiation (see 5.3.1) or a coherent diode beam (Koechner, 1999; Powell, 1998; Svelto, 1998; Siegman, 1986).

As is seen from Table 5.9, the Nd:YAG laser can generate four main wavelengths: 1064 nm, 1318 nm, 1444 nm, and 946 nm. With non-linear optics (see Section 5.4.5) the spectrum of possible generated wavelengths can be even larger, starting from ultraviolet up to near infrared with variable absorption in water – see Fig. 5.11. Flashlamp-pumped as well as diode-pumped Nd:YAG lasers found very wide use in many applications. Therefore many other matrices were investigated for the neodymium ion. Over the years, the Nd^{3+} ion was used successfully as activator for many tens of matrices, such as YLF (Nd:$LiYF_4$), $YAlO_3$ (Nd:YAP; Nd:$YAlO_3$), KGW (Nd:$KGd(WO_4)_2$), GSGG (Nd:Cr:GSGG), YVO_4 (Nd:YVO_4), $GdVO_4$ (Nd:$GdVO_4$), etc. (Weber, 1999). Their application in medicine is a question for the future.

Table 5.9 Nd:YAG laser characteristics

Material		Nd:YAG		
Matrix		$Y_3Al_5O_{12}$ (YAG) crystal or ceramics		
Active ions		Nd^{3+}		
Main used wavelength		1064.1 nm; 1318 nm; 1444 nm; 946 nm		
Harmonics wavelengths		532 nm, 354 nm, 266 nm, 213 nm		
Level scheme		4 (except for 946 nm – 3 level)		
Photon energy for 1064 nm		1.86×10^{-19} J, 1.17 eV		
Lifetime of upper laser level		240 μs		
Main pumping bands		750 nm, 800 nm, 880 nm		
Operation mode	CW Arc Kr	Free-running	Q-switched	Mode-locked
Pump mechanism	Lamp Laser diode			Xe flashlamp Laser diode
Length of pulse		100 μs–10 ms	1–100 ns	10–500 ps
Generated energy		5 J	1 J	0.01–50 mJ
Repetition rate		1 Hz–100 kHz	< 50 kHz	1–100 Hz
Cooling system	Water	Water	Water	Water
Medical applications		Ophthalmology, neurology, otorhinolaryngology, surgery		



5.11 Nd:YAG laser emission and its harmonics on the basis of the absorption of radiation in water.

Table 5.10 Other matrices for neodymium-doped lasers

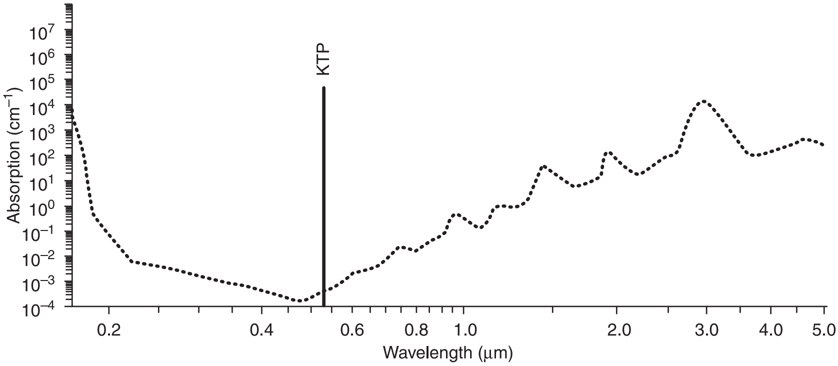
Matrix	Lifetime (μs)	Laser emission (nm)	Characteristics
$Y_3Al_5O_{12}$ (YAG)	260	1064	Mostly used matrix for Nd^{3+} (Singh *et al.*, 1974; Powell, 1998; Kaminskii, 1981)
$YAlO_3$ (YAP, YAlO)	156	1080	Anisotropic material with properties similar to YAG (Kaminskii, 1981; Jelinek *et al.*, 1988; Shen *et al.*, 1989)
YVO_4	100	1064	Material with large gain (O'Connor, 1966; Zhang *et al.*, 1999; Agnesi *et al.*, 2004)
$GdVO_4$	95	1063	Raman active crystal with extreme absorption (Qin *et al.*, 2002; Shen *et al.*, 2004; Rimington *et al.*, 2004)
$KGd(WO_4)_2$ (KGW)	130	1067	Raman active crystal (Kaminskii *et al.*, 1980; Cerny *et al.*, 2004)
$LiYF_4$ (YLF)	480	1047	Medium with long lifetime, it is suitable for pulsed regime (Powell, 1998; Koechner, 1999)
Phosphate glass	330	1054	Broad band active medium suitable for short pulse amplification (Powell, 1998; Koechner, 1999)

The properties of lasers most used for Nd:YAG applications are summarized in Table 5.9; a comparison of other neodymium-doped materials is shown in Table 5.10.

5.4.5 KTP laser

The KTP laser is in reality a Nd:YAG laser whose beam is directed through a non-linear KTP (potassium titanyl phosphate – $KTiOPO_4$) crystal to produce a beam in the green visible spectrum. The radiation from the so-called KTP laser is the second harmonic from the Nd:YAG laser working on the wavelength 1.064 μm (see above).

Potassium titanyl phosphate is a non-linear optical material that can be used for a variety of frequency conversion applications (both Type I and II), Bragg stabilization, and phase modulation. It has properties that make it unique for frequency-doubling Nd-doped systems emitting near 1064 nm – it has large non-linear optical coefficients $d_{31} = 6.5$ pm/V, $d_{32} = 5.0$ pm/V, $d_{33} = 13.7$ pm/V, $d_{24} = 7.6$ pm/V, $d_{15} = 6.1$ pm/V, low absorption, wide transmission range (350–4500 nm), and also a wide acceptance angle.



5.12 Wavelength generated by Nd:YAG/KTP laser on the basis of the absorption of radiation in water.

Its relatively short wavelength at 532 nm ensures low absorption in water (Fig. 5.12) and high affinity for oxyhemoglobin (see Fig. 1.1), making it ideal for photoablation and photocoagulation. It is used to treat a number of conditions in dermatology (Chapter 14), including port wine stains (PWS), hemangioma, telangiectasia, spider nevi and red scars, and also in urology (Chapter 16) – prostatectomy, and ophthalmology (Chapter 13) – diabetic retinopathy. For example, CW system, intracavity frequency-doubled Nd:YAG lasers generate 10 W of green power. CW-pumped, intracavity-doubled, and Q-switched Nd:YAG lasers generate 20 W of green output. Efficient intracavity-doubling of flashlamp-pumped systems with KTP has led to the production of >10 mJ green pulses in a single transverse mode at 10 Hz repetition rate. Pulsed configuration 50% extracavity doubling efficiency gives 200 mJ in 120 μs green pulses, while intracavity doubling of diode-pumped Nd:YAG and Nd:YVO_4 lasers with 3–7 mm long KTP crystal has resulted in >10 mW of green power for only 200 mW of optical pump power (corresponding to 1 W of electrical power).

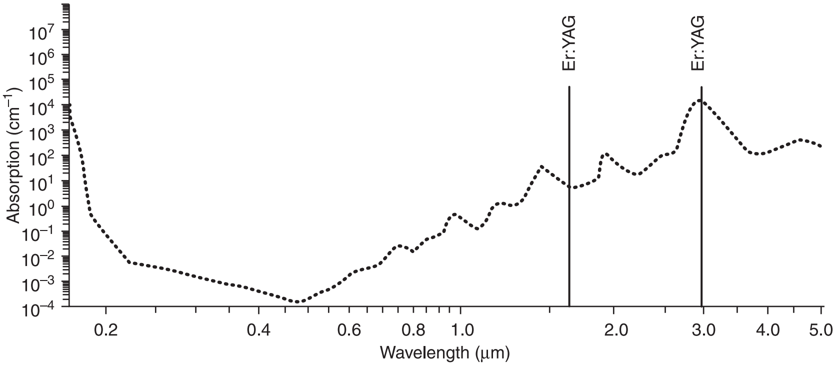
5.4.6 Er-doped lasers

Erbium lasers are systems in which the rare earth element Er^{3+} constitutes the active ion in a matrix such as YAG, YAP (yttrium aluminum perovskite), YLF ($LiYF_4$), YSGG, and glass (Zharikov *et al.*, 1975; Barnes *et al.*, 1986; Dinerman and Moulton, 1994; Tikerpae *et al.*, 1999; Young *et al.*, 2004). An overview of important Er-doped materials is presented in Table 5.11. Their attractiveness resides in the wavelengths generated. There are two groups of very interesting wavelengths corresponding to these active materials: one in the region of 2.7–3 μm (Cr:Tm:Er:YAG, Er:Cr:YSGG, Er:YAG), and the second from 1.5 μm to 1.7 μm (Er:glass, Er:YAP, Er:YLF). Radiations with wavelengths in the first group are strongly absorbed by water because of atomic resonances; the active materials from the second group generate wavelengths which belong to (1.5 μm) or are very near (1.66 μm, 1.7 μm) a very useful part of the spectrum called the 'eye safe' region, which poses very little hazard to the human eye.

One of the more interesting active materials from the first group is Er:YAG, due to the coincidence of its generated wavelength with the absorption peak of water (optical absorption >3000 cm^{-1} – see Fig. 5.13). The operation of the Er:YAG laser at room temperature was discovered in 1975. The active medium was highly doped – the erbium ion concentration was 50%. The laser emission occurs at 2940 nm. As a laser material (see Table 5.12 for Er:YAG material parameters summary) it is not very convenient, because the lower level has a much longer lifetime (2 ms) than the upper level (0.1 ms). Therefore higher pumping is needed to run the laser. The pumping is accomplished by xenon flashlamps as well as by InGaAs laser diodes at 963 nm. The Er:YAG found its main application due to its generated wavelength and its optical absorption in water (> 3000 cm^{-1}). For the other active media in this region (Cr:Tm:Er:YAG, Er:Cr:YSGG with the generated wavelengths 2697 nm and 2796 nm, respectively) the absorption in water is not on the maximum of the curve (which gives the possibility of delivering this radiation by special low-hydroxyl-fused-silica fibers), but still it is very high. Er:YAG can

Table 5.11 Erbium-doped lasers

Laser material	Lifetime (ms)	Laser emission (nm)	Characteristics
Er:$Y_3Al_5O_{12}$ (YAG)	0.1	1645	Efficient resonantly pumped eye-safe erbium laser (erbium doping < 0.5 at.%) (Setzler *et al.*, 2005)
Er:$Y_3Al_5O_{12}$ (YAG)	2	2940	Lasing at the water absorption maximum (erbium doping > 30 at.%)
Cr:Tm:Er:$Y_3Al_5O_{12}$ (CTE:YAG)	2	2697	High water absorption, special fibers for delivery are available (Barnes *et al.*, 1997)
Er:$Y_3Sc_2Ga_2O_{12}$ (Er:YSGG)	1.3	2796	Large absorption in water, higher repetition rate than Er:YAG (Dinerman and Moulton, 1994)
Er:$YAlO_3$ (YAP, YAlO)		1666	Polarized output
Er:YVO_4	5	1600	Material with large gain, possible diode pumping (Sulc *et al.*, 2008)
Er:$LiYF_4$ (YLF)		1736	Polarized output
Er:Glass	7	1540	Efficient eye-safe laser, fiber laser



5.13 Er:YAG laser emission on the basis of the absorption of radiation in water.

Table 5.12 Er:YAG laser characteristics

Material			Erbium:YAG
Matrix			$Y_3Al_5O_{12}$ (YAG)
Active ions			Er^{3+}
Wavelength		2940 nm	1645 nm
Level scheme		4	3
Photon energy		6.76×10^{-20} J	1.21×10^{-19} J
Lifetime of upper laser level		100 μs	1.5 ms
Main pumping bands		750 nm, 800 nm, 880 nm	1470 nm, 1532 nm
Operation mode	Free-running	Q-switched	Free-running
Pumping	Flashlamp, InGaAs diode laser		Resonant pumping
Length of pulse	100 μs–1 ms	60 ns	
Generated energy	0.1–5 J	50 mJ	
Repetition rate	0.1–50 Hz	< 50 kHz	
Cooling system	Water	Water	
Medical applications	Dentistry, bone surgery, dermatology, ophthalmology		

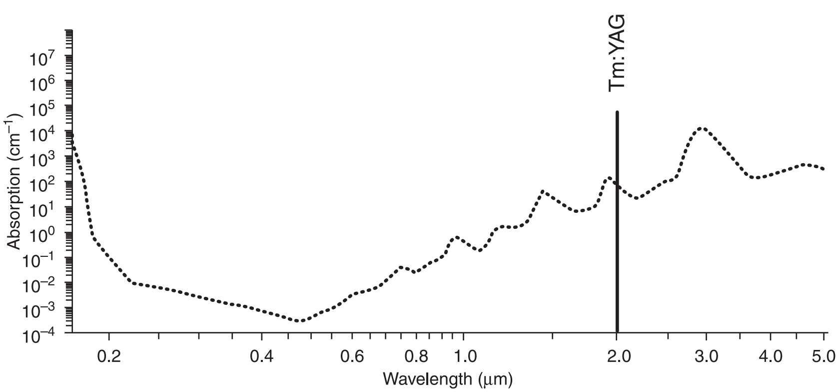
also lase at the second wavelength (1645 nm) but, instead of flashlamp or diode laser pumping, resonant pumping with the wavelength 1535 nm must be used for obtaining the population inversion. Er:YAG lasers with the wavelength 2.9 μm have been used for laser resurfacing of human skin, treating of acne scarring, deep rhytides, and melasma. When compared with the CO_2 laser, the erbium laser is gentler because the doctor can treat layers of skin far thinner than with the CO_2 laser. The erbium laser light works by vaporizing the outer layers of skin to cause skin contraction underneath, and some evidence has indicated it may even stimulate the production of the body's own collagen.

In addition, the 2.9 μm radiation of Er:YAG lasers is also absorbed by hydroxyapatite (see Fig. 1.1), which makes it a good laser for cutting bone as well as soft tissue. Bone surgery applications have been found in oral surgery, dentistry, implant dentistry, and otolaryngology. Er:YAG lasers are also safer than carbon dioxide lasers for the removal of warts, because human papillomavirus (HPV) DNA is not found in the laser plume. So, the Er:YAG laser is very useful in dentistry, dermatology, urology, and bone surgery.

From the second group of active media, Er:glass, generating the wavelength 1535 nm, has great importance. It is pumped by flashlamp, and is also used in dermatology for removal of wrinkles, acne, scars, and pigmented lesions, age-spots, sun-spots and freckles, complexion improvement and reducing stretch marks (parameters: 80 mJ, 5 or 10 ms length of pulse, 1 Hz).

5.4.7 Tm-doped lasers

Development of room-temperature solid-state lasers in the 2 μm spectral range received renewed attention at the end of the 1990s because of potential applications in medicine and optical communications. A significant absorption band of water and carbon dioxide around 2 μm wavelength (water vapor maxima for $\lambda = 1.88$ μm, 1.91 μm, and 2.14 μm; carbon dioxide for $\lambda = 1.96$ μm, 2.01 μm, and 2.06 μm) induced researchers to look for laser-generating radiation in this region. Laser radiation from this spectral range can be used also in radar and Light Detection And Ranging (LIDAR) technology for applications such as distance measurement, determining the composition of the atmosphere, measuring the speed of moving air masses, and, due to its high absorption in water (see Fig. 5.14), in medicine. Suitable active media for the construction of lasers generating radiation in this region are materials (matrix YAG, YAP, $GdVO_4$, YLF, Sc_2O_3, YSGG, etc.) doped with the trivalent lanthanide rare-earth ion of



5.14 Tm:YAG laser emission on the basis of the absorption of radiation in water.

Table 5.13 Thulium-doped lasers

Laser material	Lifetime (ms)	Laser emission (nm)	Characteristics
Cr:Tm:$Y_3Al_5O_{12}$ (YAG)	10	2020	Efficient flashlamp-pumped thulium laser (Quarles *et al.*, 1990)
Tm:$Y_3Al_5O_{12}$ (YAG)	10	2020	Efficient diode-pumped thulium laser (Li *et al.*, 1999)
Tm:$YAlO_3$ (YAP, YAlO)	6	1870–2036	Tunable diode-pumped thulium laser with polarized output (Cerny *et al.*, 2006b)
Tm:$GdVO_4$	3	1860–1990	Material with large gain, suitable for diode pumping (Cerny *et al.*, 2006a)
Tm:$LiYF_4$ (YLF)	16	1910–2070	Polarized output (Schellhorn, 2008)
Tm:Glass	2–5	1934	Efficient fiber laser

thulium (Tm^{3+}). An overview of lasers with trivalent Tm^{3+} ions is presented in Table 5.13.

In the beginning the thulium lasers were pumped by flashlamps (Quarles *et al.*, 1990). Due to the fact that Tm active medium can be described by a quasi-three-level scheme and the terminal laser level of Tm^{3+} ions is separated from the ground state by a Stark splitting only (of the order of 10^2–$10^3\,cm^{-1}$), the early laser demonstrations were performed at cryogenic temperatures in order to reduce the Boltzmann population of the lower laser level. The efficient generation of thulium laser radiation at room temperature was achieved by the addition of a sensitizer ion such as Cr^{3+} into the active medium. The Cr^{3+} ion has wide absorption bands in the 400 and 500 nm regions and therefore is useful for xenon flashlamp pumping. The excited Cr^{3+} ions transmit their energy to Tm^{3+} ions in a process called cross-relaxation. The cross relaxation is a near-resonant, nonradiative process in which a single TM^{3+} ion in excited state generates two TM^{3+} ions in the upper laser level (Quarles *et al.*, 1990). The output energy obtained from those types of lasers was in the range of units of Joules. Tm:YAG and Tm:YAP lasers were working in a free-running as well as a Q-switched regime. The main characteristics of the Tm:YAG crystal and laser are summarized in Table 5.14.

Another possibility of pumping is coherent, by laser radiation. The first-generation pumping of the Tm:YAG laser was reached by a Ti:sapphire system tuned for the needed wavelength. After laser diodes in the required region appeared, many laser systems were investigated. For this type of pumping the sensitizer is not needed.

Table 5.14 Tm:YAG laser characteristics

Material	Chrom:Thulium:YAG	
Matrix	$Y_3Al_5O_{12}$ (YAG)	
Active ions	Tm^{3+} with the co-dopant Cr^{3+}	
Wavelength	2020 nm	
Photon energy	9.83×10^{-20} J	
Fluorescence lifetime	~10 ms (at room temperature)	
Spectral linewidth	0.40 nm, cm^{-1}	
Main pumping bands	430 nm, 600 nm, 680 nm, 780 nm	
Operation mode	Free-running	Q-switched
Pump mechanism	Flashlamp, diode	
Length of pulse	300–800 μs	100 ns
Generated energy	< 3 J	Units of J
Repetition rate	Units of Hz	Units of Hz
Cooling system	Water	Water
Medical applications	Urology, dentistry	

The advantages of thulium-doped active material are broad emission lines (it is possible to cover a range of wavelengths from 1800 to 2200 nm) and high quantum efficiency for diode pumping, enabled by resonant ion–ion interactions. Another advantage of this ion is its long lifetime in the excited state (up to 11 ms for Tm:YAG); the active element with ions of Tm^{3+} is suitable for energy storage and generation of Q-switched pulse (Powell, 1998; Sorokina and Vodopyanov, 2003).

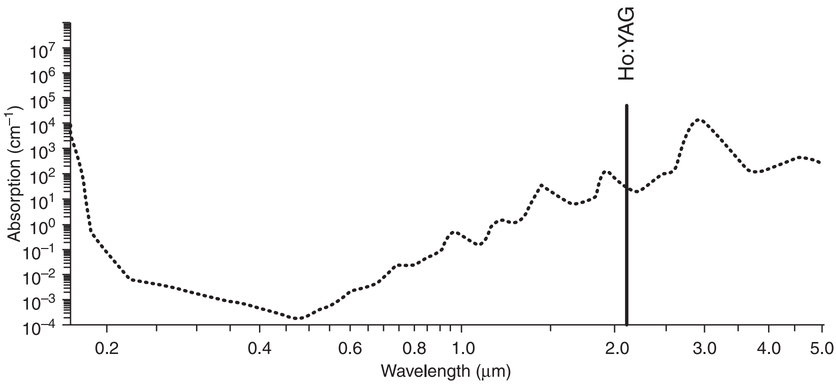
Conventional materials with Tm^{3+} ions are Tm:YAG and Tm:YAP. It has been investigated with flashlamps as well as diode pumping. As a result, power of dozens of watts was obtained (Stoneman and Esterowitz, 1990, 1995; Beach *et al.*, 1996; Honea *et al.*, 1997; Bollig *et al.*, 1998; Tsunekane *et al.*, 1999; Elder and Payne, 1998a,b; Li *et al.*, 1999; Matkovskii *et al.*, 2002). Because the absorption bands of these materials are narrow, a special laser diode with convenient pumping wavelength has to be chosen to reach the optimal output efficiency.

5.4.8 Holmium lasers

Holmium ion is another of the lanthanide rare-earth elements used for the generation of laser radiation. The first laser emission obtained from the holmium-doped YAG crystal at 2.1 μm was obtained at liquid nitrogen temperature in 1962 (Johnson and Soden, 1962) due to the very narrow absorption lines of holmium ion. The wavelength 2 μm was so attractive (due to the atmospheric transmission properties and eye-safe nature of this radiation) that other possible pumping mechanisms were researched with the goal of operating this laser at room temperature. This was achieved with the help of a sensitization mechanism by chromium and thulium ions. The CTH:YAG laser (chromium, thulium, holmium YAG, Cr:Tm:Ho:YAG – see Table 5.15 for details) became an efficient source of laser energy at this temperature (Johnson *et al.*, 1965; Antipenko *et al.*, 1988; Quarles *et al.*, 1989, 1990; Bowman *et al.*, 1991). Instead of a YAG matrix, YAP, YSGG and others also were used for holmium ion (also with Cr and Tm, or with Tm only as the sensitizer) (Alpatev *et al.*, 1998; Jani *et al.*, 1991; Barnes, 1996). The wide absorption spectrum of CTH:YAG crystal (0.2–1.7 μm) made it possible to use flashlamp as well as coherent pumping. CTH:YAG lasers were pumped by xenon flashlamps or by krypton, argon, dye or semiconductor lasers. The radiation obtained generally has the wavelength 2.0963 μm. In a dispersion resonator, up to nine wavelengths in the region from 2.0803 to 2.1275 μm were obtained (Bowman *et al.*, 1991). With the development of the laser diode came the renaissance of Ho lasers. The properties of other laser matrices such as YLF, YAP, YVO_4 or $GdVO_4$ having holmium ions as an active ion were investigated. Using a diode-pumped Tm:Ho:$YAlO_3$ laser, operating at room temperature, emission at wavelength 2.12 μm was obtained (Elder and Payne, 1998a). Tunable laser sources operating in the 2 μm wavelength are useful for many applications, such as LIDAR for atmospheric pollution monitoring, remote sensing, rangefinders, wind shear detection and medical applications (see the absorption of its wavelength in water (Fig. 5.15)). Additionally, 2 μm lasers can be used as pump sources, which are applicable to non-linear optics research, such as a 3–12 μm optical parametric oscillator. CW output power of 270 mW has been demonstrated using a diode-pumped b-axis Tm(4.2%), Ho(0.28%):$YAlO_3$ with emission wavelength of 2.12 μm operating at room temperature; the corresponding YLF is chosen as a host crystal because of its long pump integration time, excellent

Table 5.15 CTH: YAG laser characteristics

Material	Chrom:Thulium:Holmium:YAG	
Matrix	$Y_3Al_5O_{12}$ (YAG)	
Active ions	Ho^{3+} with the co-dopant Cr^{3+}, Tm^{3+}	
Wavelength	2100 nm	
Photon energy	1.86×10^{-19} J	
Fluorescence lifetime	3.6 ms (at room temperature)	
Main pumping bands	430 nm, 600 nm, 680 nm, 780 nm	
Operation mode	Free-running	Q-switched
Pump mechanism	Flashlamp	
Length of pulse	200–300 μs	100 ns
Generated energy	< 3 J	Units of J
Repetition rate	Units of Hz	Units of Hz
Cooling system	Water	Water
Medical applications	Urology, dermatology	



5.15 Ho:YAG laser emission on the basis of the absorption of radiation in water.

optical damage resistance, lack of thermally induced birefringence, and linearly polarized output.

5.5 New solid-state laser development

The lasers presented in this section are systems which have come into production in recent years and may in the near future also be used for medical applications (disc or slab lasers giving enough energy/power for surgery, and the small design of the microchip laser leading to potential use for diagnostics). At the end of the section a summary of lasers with new active media generating radiation in the mid-IR region is presented. These lasers may be useful in new medical treatment or diagnostics.

5.5.1 Disc and slab lasers

With the increase of solid-state lasers' average output power, heat generation inside the laser active medium, connected with the pumping process and laser emission, has a significant influence on laser operation. The combination of volumetric heating of the laser active medium by pumping radiation, together with simultaneous heat dissipation to the surrounding active medium, leads to inhomogeneous temperature distribution inside the system. This causes spatial and temporal modulation of the temperature-dependent properties of active medium (refractive index, lifetime in an upper laser level, etc.), influencing the behavior of the laser. For stable operation these phenomena should be either eliminated or compensated.

In the standard laser cavity arrangement heat is removed from a cylindrical laser rod through the cylinder side wall, which is in contact with the cooling medium (usually water or metal). The symmetrical pumping of the active medium gives a radial temperature field. Subsequent modulation of the refractive index appears as a *thermal lens* (Koechner, 1999). The temperature gradient induces mechanical stress, which causes birefringence of the active environment, and if the stress reaches the fracture limit it can result in mechanical damage to the laser rod (Koechner, 1999; Lii *et al.*, 1995; Chen, 1999). There are several methods which can reduce these negative effects.

The influence of the thermal lens can be partially compensated by the special oscillator arrangement (Kudryashov and Weber, 1999; Hodgson and Weber, 2005). However, if the thermal lens contains some uncorrectable part, it can cause significant diffraction losses and laser beam quality degradation. To decrease these effects it is possible to use a special geometry/shape of the active medium – a slab – in which the laser beam does not pass through the active medium along the axis of the temperature field, but propagates zig-zag at some angle to this axis using internal reflections inside the slab. This arrangement was effective even for flashlamp-pumped SSL (Martin and Chernoch, 1972; Chernoch *et al.*, 1971), but the significant expansion of this approach used to eliminate the negative thermal effects is connected with diode-pumped SSLs (Welford *et al.*, 1991; Bernard and Alcock, 1993; Burnham *et al.*, 1994; Lii *et al.*, 1995; Shine *et al.*, 1995; Rutherford *et al.*, 2000a,b, 2001).

The greater the angle between the axis of the laser beam and the axis of the thermal field, the less are the effects of temperature gradients on the laser beam. One application of this idea is to use active medium in the form of a thin disc (thickness in fractions of a millimeter). In order to cool such a thin disc, the base of the disc is in perfect thermal contact with a strongly cooled heatsink (Giesen *et al.*, 1994; Brauch *et al.*, 1995; Vetrovec *et al.*, 2003). This base also serves as a reflecting surface. A significant temperature gradient then exists only along the axis of the disc. The radial temperature change is negligible in the case of homogeneous pumping. A wavefront laser beam which turns at right angles or at a small angle to the ‘active mirror’ is not distorted in the transverse direction. On the other hand, the small thickness of thin-disc active medium reduces its absorption and gain. To achieve a good performance of a thin-disc laser requires a new geometry of pumping and disc resonator, ensuring multiple passes of both the pump as well as the generated laser radiation through the disc. This arrangement allows the realization of reliable, highly efficient, diode-pumped kilowatt-class SSL generating an excellent-quality laser beam (Schlueter, 2005).

5.5.2 Fiber lasers

Another way to ensure effective heat dissipation from the laser active medium, maintaining the generated laser beam quality even for very high average pumping power, is to use the active medium in the form of an optical fiber. The technology of optical fibers and guided waves was developed and used in optical communications, and in last ten years has also been successfully adopted for laser construction. In the case of optical fiber used as a laser active medium, the ratio between the surface area useful for active medium cooling and the active medium volume is inversely proportional to the radius of the fiber. As the active medium becomes thinner and longer, the effectiveness of heat dissipation increases and negative thermal effects are reduced. It has been shown that air-cooled glass optical fiber can dissipate without damage up to 150 W of heat per meter of length (Nilsson *et al.*, 2003). Together with the guiding effect of optical fiber, this makes it possible to construct fiber lasers whose output exceeds 1 kW with excellent beam profile, using only an air-cooling system (Gapontsev and Krupke, 2002; Gapontsev *et al.*, 2005; Jeong *et al.*, 2005). Thanks to all-fiber technology without any free-space optics it is possible to build very compact and maintenance-free fiber lasers compatible with fiber delivery systems. Using Yb, Er, or Tm doped fibers as active fibers, wavelengths around 1 μm, 1.5 μm, and 2 μm are available with continuous power exceeding 100 W from a 'shoe-box-sized' system.

A possible restriction of fiber lasers can be the glass matrix, which, due to the damage and non-linear effects, limits peak power generated by this type of solid-state lasers. The threshold for glass damage is approximately 10^{10} W/cm^2. A single-mode laser with core diameter 10 μm could thus theoretically generate/transmit radiation with power in the order of 1000 W (Xu *et al.*, 2003). Further increase in peak power is possible only at the cost of laser beam quality degradation (Chen *et al.*, 2005) or by use of crystalline fibers (Kaminskii, 1996).

5.5.3 Microchip lasers

Diode pumping of solid-state laser active medium enables significant miniaturization of the entire laser system. This is possible because, unlike flashlamp emission, the laser diode radiation can be concentrated into a very small volume (<<1 mm^3). Using a suitable active medium, sufficient absorption of excitation radiation can be reached in millimeter distance. If such a longitudinally pumped active medium has the mirrors deposited directly on its front surfaces, it creates a microchip laser.

The term microchip laser was first used in 1989 in connection with a submillimeter Nd^{3+} laser, operating at wavelength 1064 nm (Zayhowski and Mooradian, 1989a,b; Zayhowski *et al.*, 1989). For pumping this laser, Ti:sapphire radiation tuned to the maximum absorption of Nd^{3+} near 808 nm was used. In these first experiments the potential of this concept was demonstrated: high efficiency, emissions in single longitudinal mode of resonator, subnanosecond pulse generation and high system stability.

During recent years, generation of a microchip laser pumped by a laser diode was achieved. Other elements were implemented inside the microresonator (active and passive Q-switches, non-linear crystals, elements for wavelength control, etc.) (MacKinnon and Sinclair, 1994; Zayhowski, 1999; Chen and Lan, 2002; Feldman *et al.*, 2003). Also other emission wavelengths of the microchip laser have been tested: 1 μm (Yb^{3+}) (Burns *et al.*, 2002; Dascalu *et al.*, 2003), 1.3 μm (Nd^{3+}) (Fluck *et al.*, 1997; Malyarevich *et al.*, 1998), 1.5 μm (Er^{3+}) (Denker *et al.*, 2003; Hamlin *et al.*, 2004), 1.9–2 μm (Tm^{3+}) (Lescroart *et al.*, 1997; Wyss *et al.*, 1998; Zagumennyi *et al.*, 1999), 2.1 μm (Ho^{3+}) (Izawa *et al.*, 2000).

The mean output power of microchip lasers now significantly exceeds the value of 1 W. In Q-switching regime, peak power of up to 1 MW has been achieved. Microchip lasers are mainly used as energy-saving compact stable sources of laser radiation in a portable system for measuring distance, the lighting of the 3D visualization of terrain, spectroscopy, etc. (Molva, 1999; Zayhowski, 2003; Sennaroglu, 2007).

5.5.4 New mid-infrared solid-state lasers

Due to the requirements of medical diagnosis and treatment (and also demand from other possible applications, such as spectroscopy, remote-sensing, trace gas detection, etc.), new laser sources – preferably tunable – are sought. Special interest is now devoted to the spectral range 2–6 μm, where molecules of water, carbon dioxide, nitrous oxide, carbon monoxide, methane, etc. have absorption. The detection of low concentrations of these gases for the purpose of medical diagnostics is possible with the use of mid-infrared laser radiation. Laser sources based on the transition-metal-doped II–VI compounds (DeLoach *et al.*, 1996; Page *et al.*, 1997; Sorokina and Vodopyanov, 2003; Basiev *et al.*, 2005) are advanced as alternatives to the gas laser (CO – wavelength 4.8 μm) or sources using optical parametric generation or Raman effects.

Furthermore, the ultra-broad gain bandwidth of some laser crystals from this group allows ultrashort pulses in the picosecond or even femtosecond region to be generated, which can provide new application possibilities. Examples include Cr:ZnSe, Cr:ZnS, Fe:ZnSe or Dy:$PbGa_2S_4$ lasers (Sorokina and Vodopyanov, 2003; Basiev *et al.*, 2005; Jelínková *et al.*, 2011; Doroshenko *et al.*, 2010; Sulc *et al.*, 2010; Basiev *et al.*, 2011a; Myoung *et al.*, 2011; Basiev *et al.*,

Table 5.16 New mid-infrared solid-state lasers

Laser material	Lifetime at 300 K	Laser emission	Characteristics
Cr:ZnSe	2–10 μs	2100–2800 nm 2400 nm peak emission	CW output power 6.5 W (Renz *et al.*, 2012) Pulsed regime – 14 mJ in 120 μs long pulse (Jelínková *et al.*, 2007)
Cr:ZnS	4.5 μs	2250–2650 nm 2350 nm peak emission	a) CW output power 25 mW (Sorokina *et al.*, 2002) b) 3.7 nJ in 69 fs long pulse (Sorokin *et al.*, 2012)
Fe:ZnSe	300 ns	3950–5050 nm 4470 nm peak emission	Gain switch regime, 420 mJ @ 77 K, 1 μJ in 5 ns @ 300 K, 5 mJ in 20 ns @ 300 K (Myoung *et al.*, 2011)
Dy:$PbGa_2S_4$	2.3 ms	a) 4 μm, 4.3 μm, and 4.6 μm (according to pumping and resonator mirrors); b) tunable through 4.28–4.34 μm; c) 4.29 μm	a) Output energy 7 mJ in 80 μs pulse (Jelínková *et al.*, 2011); b) 2.6 mJ (Doroshenko *et al.*, 2012) c) Energy 90 μJ in 4 ms pulse, mean output power 1.8 mW (Sulc *et al.*, 2010)

2011b; Sorokin *et al.*, 2012). The properties of these lasers are summarized in Table 5.16.

5.6 Conclusion

In this chapter a brief introduction to solid-state laser systems used in medical applications was presented. It was shown that laser devices based on an optically transparent solid insulator doped with ions from the transition metals or lanthanides can offer properties which are suitable for a laser active medium. The lasers based on this kind of active media offer most of the parameters important for a highly efficient, versatile, low-maintenance, durable, and compact laser system. Thanks to the properties of solid-state active media, briefly described in this chapter, the properties of solid-state laser radiation can cover a broad range of parameters: emission wavelengths from the visible region to mid-infrared, pulse operation with high energy and short pulse lengths, continuous operation with very high mean power, etc. There are several solid-state lasers which have been successfully used in medical applications for many years, such as Nd:YAG, Er:YAG, and Alexandrite. We have also tried to show that, even though the history of solid-state lasers is now more than 50 years old, the development of solid-state lasers is very progressive, and in the near future we may expect even further improvements in solid-state lasers and their further penetration into applications including medicine.

For additional reading on solid-state lasers, we can recommend Koechner's book (Koechner, 2006), which describes in detail most aspects of solid-state laser technology and engineering. A deeper view into solid-state active media physics can be found in Powell's monograph (Powell, 1998). Some new interesting aspects of solid-state laser physics and technology can be found in books edited by Sennaroglu or by Sorokina and Vodopyanov (Sennaroglu, 2007; Sorokina and Vodopyanov, 2003). Finally, to anybody who is interested in solid-state lasers and in lasers in general, we can recommend the famous Svelto and Siegman textbooks (Siegman, 1986; Svelto, 1998).

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5.8 Bibliography

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