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Neodymium doped lithium yttrium fluoride ($Nd:YLiF_4$) lasers

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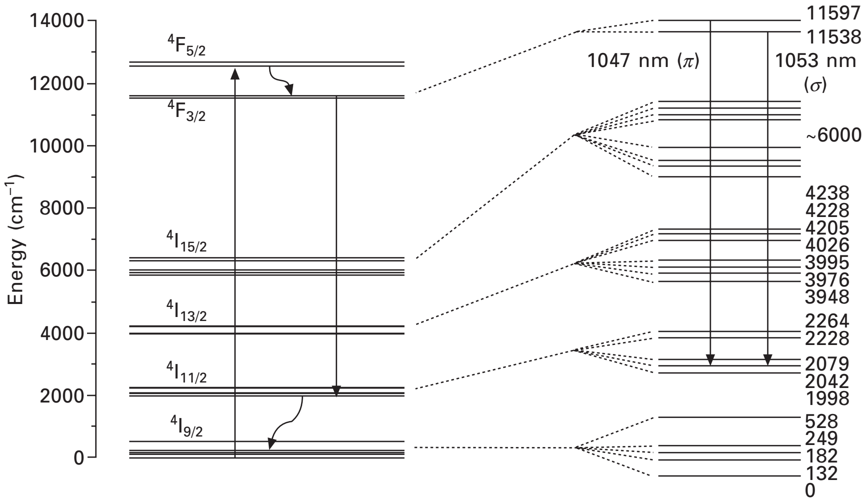
Abstract: As a laser material, the neodymium doped lithium yttrium fluoride laser shows some very important and favorable characteristics when it comes to laser beam quality, efficient high-energy pulsed operation and parametric processes, amongst other applications. In this chapter we will discuss several approaches that have resulted in efficient, high-quality laser beams usually through decreasing the influence of the structural drawbacks of the YLF host whilst taking advantage of its favorable optical properties.

Key words: laser material, solid-state lasers, rare earth lasers, neodymium lasers, diode-pumped lasers, laser resonators.

12.1 Introduction

Since the first construction of a neodymium doped lithium yttrium fluoride laser ($Nd:YLiF_4$ or more briefly Nd:YLF) in 1981, its main advantages with respect to the already well-known and widespread oxide laser Nd:YAG (yttrium aluminum garnet, $Y_3Al_5O_{12}$) have been recognized (Pollak *et al.*, 1982). These are large upper state lifetime, weak thermal lensing and natural birefringence (Vanherzeele, 1988). Thermal conductivity, absorption and emission cross-section are roughly half those of the YAG host at similar doping level (Ryan and Beach, 1992; Pfistner *et al.*, 1994). The birefringence causes two emission lines, one at 1047 nm and another at 1053 nm that matches the wavelength transition of Nd^{3+} glass amplifiers commonly used in high pulse energy systems and laser fusion facilities. The 1047 nm emission is obtained for light polarized parallel to the crystal *c*-axis (π-polarization) and the 1053 nm emission for light polarized perpendicular to the *c*-axis (σ-polarization). Both transitions originate from the $^4F_{3/2}$ upper laser level and terminate at the second Stark splitting of the $^4I_{11/2}$ lower laser level (see Fig. 12.1). Nd:YLF may be efficiently diode pumped around 800 nm presenting two main absorptions at 792 nm and 797 nm and a roughly 50% smaller absorption at 806 nm. The 797 nm peak absorption coefficient is higher for π-polarization than for σ-polarization and of the order of 5–10 cm^{-1} for 1 mol% of neodymium doping.

The large upper state lifetime of Nd:YLF measures more than half a



12.1 Energy level diagram of Nd:YLF (Kaminskii, 1996).

millisecond, showing potential for very large energy storage which is good for diode pumping, high peak powers and large pulse energies. However, it has been observed that under Q-switched operation, especially at low repetition rates, the system performance deteriorates (Beach *et al.*, 1993). This behavior has been attributed to quenching of the upper laser level lifetime. The strong yellow fluorescence caused by upconversion under non-lasing operation is easily observed by the naked eye and a measure for this quenching process indicating a bigger heat load, which is followed by a series of generally unwanted consequences (Fan *et al.*, 1986). Heat generation during the non-lasing transitions in Nd:YLF lasers pumped by powerful high-brightness diodes is approximately twice as high as during lasing and 30% higher than in Nd:YAG under similar pumping conditions. This is the downside of a long upper laser level lifetime in Nd:YLF: non-linear processes originating from the upper laser level become stronger (Pollnau *et al.*, 1998).

The increased heat load inside the crystal is accompanied by an adverse decrease in thermal conductivity that causes an altogether much higher temperature at the center of the pump face, thus strongly increasing stress and strain in this area. If the stress is above the sample's fracture limit, damage to the crystal might occur during instances of non-lasing operation. When compared to YAG, YLF has an approximately five times lower fracture limit. In fact it is so small that in many cases fracture in Nd:YLF has been observed simultaneously with the occurrence of thermal lensing, which makes it difficult to experimentally foresee this catastrophic damage (Bollig *et al.*, 2010).

The weak lensing in YLF can be observed under lasing conditions when upconversion loss is minimized and is a consequence of two simultaneously occurring effects: the negative refractive index change with increasing temperature and the positive lens created by end-face bulging of the laser crystal. Both contributions tend to cancel each other but the former contribution is stronger in the π-polarization, causing an altogether negative thermal lens, whereas for the σ-polarization the contribution of the negative index change is less, causing a small positive lens (Cerullo *et al*., 1992). It is this characteristic of YLF that has brought a renewed interest to this laser material, because with today's high brightness diodes the focal length of the thermal lens generated inside the crystal rapidly becomes less than the cavity length and may turn the resonator unstable. Especially in longitudinally pumped laser designs, the onset of resonator instability puts a limit to the maximum achievable output power. Therefore, thermal lensing normally sets the upper limit in terms of absorbed pump power for high-power, diode-pumped solid-state laser systems.

The low fracture limit and thermal lensing of Nd:YLF call for efficient cooling and other measures to decrease heat load and resultant strain and stress in the host material. This can be done by using a low cooling temperature to increase thermal conductivity and also crystal geometries with large cooling surface to sample volume ratios, such as long and thin rods or thin slabs. Additionally, the thermal gradient inside the rod and the resultant stress and thermal lens can be decreased by keeping the dopant concentration low to decrease upconversion and by detuning of the pump wavelength from the absorption peak, or by using larger pump spot sizes to dilute the absorption over a larger volume. However, these measures are only effective whenever high pump intensity is not an issue, such as in Q-switched laser operation.

12.2 Pumping methods of Nd:YLF lasers

12.2.1 Lamp-pumped Nd:YLF lasers

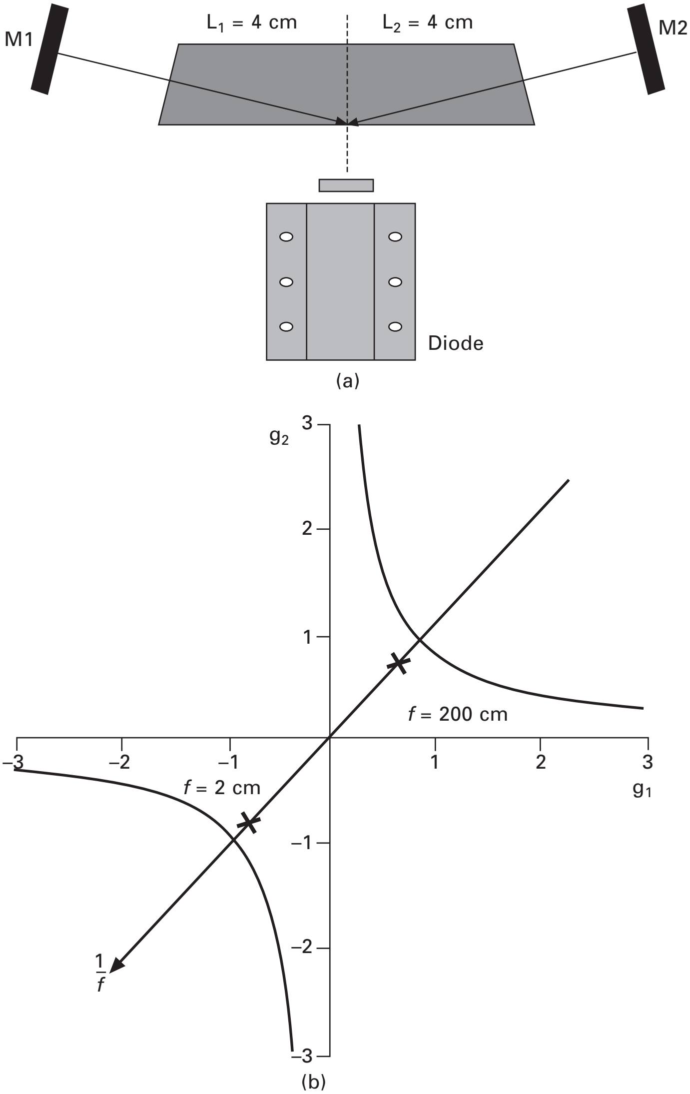
If the pump light is deposited over a relatively large volume, such as in lamp-pumped lasers, the heat gradient is automatically smaller and relatively high pulse energies and continuous (cw) powers can be obtained but efficiency and spatial beam quality are limited. A series of cavity designs have been employed that partly overcome these efficiency and spatial beam quality drawbacks of lamp-pumped lasers (Hanna *et al*., 1981). A relatively simple method to achieve fundamental mode operation in lamp-pumped laser rods is the mode-filling technique (Magni, 1986). By choosing appropriate resonator mirrors and distances between mirrors and rod, the cross-section of the fundamental mode inside the rod can be increased to a size where diffraction losses at the borders of the rod become too large for the next higher transverse mode to oscillate. Nd:YLF is especially suited for this method because of its natural birefringence and permits fundamental mode operation in standard, one-quarter-inch diameter rods; meanwhile, thermally induced birefringence limits the use of this technique in YAG rods to diameters of a couple of millimeters (Cerullo *et al.*, 1993; Wetter *et al.*, 1993). Forty watts of continuous fundamental mode output power at 1047 nm and 35 W for 1053 nm have been obtained for 7 kW of lamp pump power using this technique together with a 6.35 millimeter diameter Nd:YLF rod (Cerullo *et al.*, 1992). Eventually, for very large fundamental-mode diameters, the resonator becomes unstable as a function of TEM_{00} diameter fluctuations, a problem that can be mitigated by joining the stability zones using, for example, resonator arms of the same length, as shown in Fig. 12.2 (Cerullo *et al.*, 1993; Wetter *et al.*, 2008a).

As pointed out in the introduction, lamp-pumped Nd:YLF lasers are used for laser applications that need high power, high energy and good beam quality. One famous example is the OMEGA facility at the University of Rochester's Laboratory for Laser Energetics (LLE). One of the many amplifier stages used to achieve the petawatt powers and kilojoule pulse energies necessary to drive the laser fusion and high-energy-density physics experiments is an optical parametric chirped pulse amplifier (OPCPA) whose final amplification stage consists of a four-pass ring Nd:YLF laser using two flashlamp-pumped, one-inch-diameter rods. This front end produces 2.4 ns pulses of 2 J at 5 Hz (Kelly *et al.*, 2006) before the pulses get further amplified by a chain of Nd:glass amplifiers.

12.2.2 End-pumped Nd:YLF lasers

When efficiency and spatial beam quality are an issue, as in most of today's laser designs, then high pump intensity is necessary and the range of possible cavity setups is limited. High pump intensity can be achieved under diode pumping using high brightness diodes (Wetter, 2001). For example, a 50 W diode bar coupled to a 100 μm fiber of 0.22 NA that is focused into a 300 μm focal spot size has a confocal length of four millimeters and a pump intensity of 70 kW/cm^2. The small dimensions of the round pump-spot size inside the host can then be matched to the fundamental mode inside the resonator, allowing for high beam quality. This end-pumping scheme is by far the most used cavity setup for efficient and high beam-quality lasers.

Pump saturation is normally not a problem at these high pump intensities, because as soon as the lasing threshold is overcome, laser operation clamps the upper laser level population so that upon increasing the pump level the effective upper laser level lifetime decreases and the active ions can be cycled ever more quickly, increasing thereby the lasers' output power. This, in principle, permits one to decrease pump and laser mode size within the active media, permitting lower threshold and better slope efficiency as

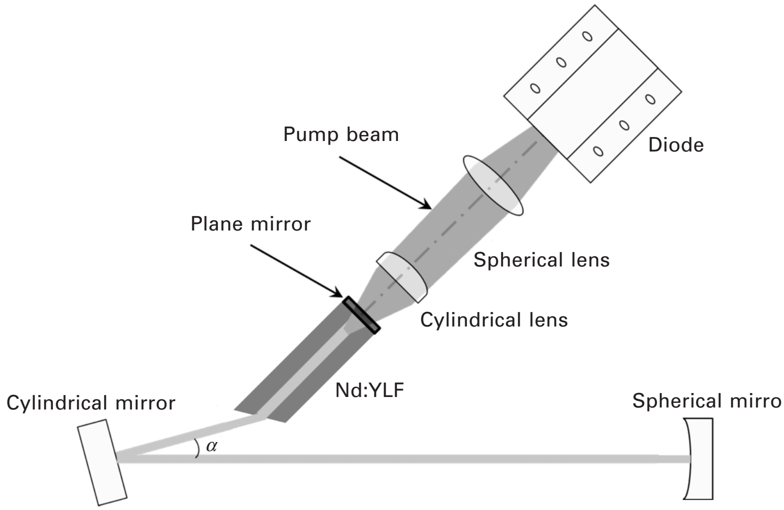


12.2 Example of joint stability zones in a side-pumped laser. (a) Simple high-efficiency resonator with equal distance between crystal and mirror M1 and M2, respectively. (b) Joined stability zones of this resonator, permitting stable operation with a thermal lens ranging from 200 cm to 2 cm as a function of pump power (Wetter *et al.*, 2008a).

long as good overlap between both beams is still guaranteed. Although the thermally induced gradient does increase with smaller pump beam waists, thermal lensing is not necessarily increased because the smaller laser beam waists are less affected by this gradient. A turning point is achieved when the beam quality of the pump beam starts to decrease the overlap efficiency between pump and laser inside the absorption region. This problem can be circumvented in part if the laser is operated much above threshold, because in such a case one may depart from the optimum relation between laser mode to pump mode of 1 to 1 and choose a smaller pump mode such that the ratio becomes 2:1 at the center of the gain media, in which case good efficiency is still guaranteed for most practical pump setups. For even higher ratios, thermally induced diffraction loss becomes a problem because the thermal gradient departs from a parabolic shape across the laser beam's cross-section. It should be noted, however, that for high-gain lasers, which are operated several times above threshold, the benefit of smaller pump waists results generally only in a minor gain in efficiency even if pump overlap can be maintained. Additionally, the higher thermal gradient increases the probability of thermally induced catastrophic crystal fracture, which is particularly low in Nd:YLF (fracture limit of 40 MPa). In fact, the common 'roll-over' effect in the input–output power curve, associated with a thermal lens that is strong enough to turn the laser cavity unstable, is hardly visible with Nd:YLF crystals and most often its onset occurs practically together with the crystal's fracture. As a result, most diode end-pumped neodymium doped lasers oscillating at the fundamental wavelength operate generally only a few times above threshold, using beam waists between 200 μm and 400 μm.

The first demonstration of an end-pumped Nd:YLF laser in 1986 used a 30 mW GaAlAs single stripe diode and achieved already 38% slope efficiency at 1047 nm during cw operation (Fan *et al.*, 1986). For higher pump powers the width of the diode stripe has to be increased and the pump beam gets increasingly elliptical. It is still possible to achieve very high efficiency if these elliptical beams are correctly matched to the cavity mode. Using cylindrical cavity mirrors, an ellipticity factor of 12 has been achieved in a Brewster cut Nd:YLF crystal, matching the cavity mode to the pump beam of the 500 μm wide diode emitter (Zehetner, 1995). The authors achieved in excess of 1 W of fundamental mode cw output power at 1047 nm with 71% slope efficiency and 41.8% optical-to-optical efficiency (see Fig. 12.3).

For even higher output power, it is no longer possible to increase the width of the stripe for cooling reasons, and several stripes, generally between 10 and 60, are grown in parallel on a 1 cm wide diode array, also called a diode bar. The ellipticity of this emitter is 1:10,000 and only rather complex devices can transform this pump beam into a beam with approximately equal dimensions and quality factors in the horizontal and vertical directions (Wetter, 2001). For this reason it is generally preferred to use fiber-coupled diode bars. At one watt of output power in fundamental mode, an optical-to-optical efficiency of 50% with respect to absorbed pump power has been achieved for the 1047 nm emission (Lue *et al.*, 2010b) when pumped at 806 nm.

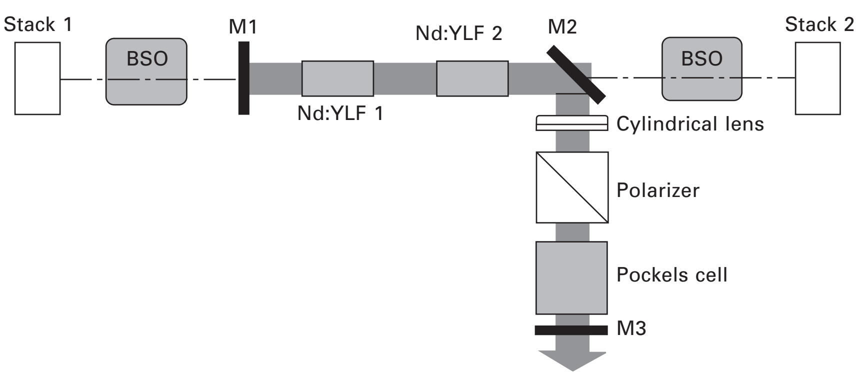


12.3 End-pumped laser cavity scheme. This folded cavity uses a cylindrical mirror in order to match laser and pump beam inside the Nd:YLF crystal (Zehetner, 1995).

An interesting scheme for high-power diode pumping is the doubly end-pumped tightly folded cavity. In this setup the gain media are pumped from both ends, preferably with fiber-coupled diodes for symmetrical beam quality. In order to place the pump-focusing optics close to the gain crystal, the cavity is folded by two mirrors that are placed close to the end-faces. Using two 100 W diodes, coupled into 600 μm diameter fibers, an optical-to-optical efficiency of 40% has been obtained for quasi-cw emission at 1053 nm (Babushkin and Seka, 1998). Given the pump beam quality factor which generally is several tens of times worse than the fundamental mode, the overlap that can be achieved in the axial direction is usually limited to no more than 1 cm. This confocal length, which equals twice the Rayleigh length, has to be enough to absorb a considerable fraction of the pump power and achieve good absorption efficiency. Therefore, the doping concentration should be enough so that the confocal range equals about three absorption lengths, which results in 95% of absorbed pump power. As a consequence, there is a large pump-induced heat load that has to be removed. By far the most common way to cool end-pumped lasers is by cooling the side faces or the barrel surface of the crystal using a rectangular or cylindrical geometry, respectively. This edge-cooling method is responsible for a radial temperature gradient that in turn causes a thermal lens which in most cases can be approximated by a parabolic profile at the center of the pump spot (Clarkson, 2001). The fundamental mode size should be less than or at most equal to the pump spot size, as outside the pump spot the lens profile departs from the parabolic shape and therefore causes aberration losses (Pfistner *et al*., 1994).

For higher output powers, the fundamental mode size inside the crystal should be increased, eventually accompanied by lower doping concentration and detuning of the pump wavelength. A careful balance of these measures resulted in 60 W cw output power at 1053 nm, 44% optical- to-optical efficiency with respect to absorbed pump power (38% overall optical efficiency) and good beam quality without observing lifetime quenching during Q-switched operation (Bollig *et al*., 2010). The authors used a doping level of 0.5% of Nd^{3+} and the pump wavelength and spot size were 806 nm and 1 mm, respectively. Using an acousto-optic modulator, Q-switched operation was achieved with repetition rates ranging from 5 kHz (pulse energy of 10.4 mJ, duration of 76 ns, 52 W of average output power) to 30 kHz.

The relatively small thermal conductivity and the small tensile strength of Nd:YLF limit the maximum output power that can be achieved with end-pumped rod designs because increase in pump power absorption means stronger thermal gradients. Increasing further the pump spot size permits higher output powers but at the expense of beam quality and laser efficiency (Beach *et al*., 1993), given the relatively low pump absorption and small stimulated emission cross-section. In order to increase pump power absorption density, a geometry has to be employed that increases the pump volume but at the same time keeps the distance from the pump spot to the cooled surface small. This can be achieved with thin, end-pumped slabs. Using a diode stack that was focused into a 0.4 mm × 12 mm pump spot size inside two 1 mm thin slabs, 127 W of cw multimode output power at 1047 nm was achieved inside a stable cavity (Li *et al*., 2007). Using an unstable cavity, shown in Fig. 12.4, the same authors achieved almost diffraction-limited cw output of 74 W with 37% optical-to-optical efficiency (Li *et al*., 2008).



12.4 Unstable folded resonator design with diffraction-limited output employing two Nd:YLF crystals pumped by two diode stacks and beam-shaping optics (BSO) (Li *et al.*, 2008).

The same authors tested electro-optic (EO) Q-switched operation and achieved 39% optical-to-optical efficiency at 10 kHz repetition rate for the fundamental wavelength of 1047 nm. The highest multimode pulse energy and duration were 25.4 mJ and 5.9 ns at 1 kHz repetition rate, whilst diffraction-limited pulse energy and duration were only slightly less, 24.2 mJ and 7 ns, respectively. Optical-to-optical efficiency at 5 kHz and 1 kHz were approximately 29% and 12% respectively.

End-pumping is also traditionally used for ultra-short pulse generation with mode-locked Nd:YLF lasers that tends to give slightly shorter pulse duration because of its broader linewidth of 1.45 nm when compared to Nd:YAG. Using an antiresonant semiconductor Fabry–Pérot saturable absorber (SESAM), 3.3 ps duration pulses with 700 mW of average output power for 2 W of pump power at 220 MHz repetition rate have been achieved (Keller *et al.*, 1992). Even broader linewidths of up to 1.9 nm are possible with mixed host crystals, as for example Nd:LuYLF that contains a mixture of 50% lutetium and 50% yttrium, generating shorter pulses than with pure Nd:YLF (Maldonado *et al.*, 2001).

12.2.3 Direct pumping of Nd:YLF lasers

The energy difference from the $^4F_{5/2}$ upper pump level in Nd:YLF, populated when using standard 805 nm diodes, to the upper laser level is 995 cm^{-1} and the energy difference from the lower $^4I_{11/2}$ laser level to the ground level is 1997 cm^{-1} (Pollnau *et al.*, 1998). Directly pumping into the $^4F_{3/2}$ emitting level therefore causes a 33% reduction in heat load caused by pump absorption. Three possible pump wavelengths are adequate for this purpose, 863 nm, 872 nm and 880 nm, corresponding to the first, second and third Stark splitting of the ground level, respectively (Lue *et al.*, 2010b). Sometimes this is also referred to as 'thermally boosted pumping' when the pump absorption transition originates from the second or third Stark level (see Fig. 12.1). However, pump absorption at these wavelengths is small, of the order of 1–3 cm^{-1} and therefore laser-to-pump beam overlap efficiency is not optimal and a large amount of pump power usually passes through the crystal without being absorbed. The latter effect can be mitigated by using clever arrangements that reimage the pump beam into the crystal, thereby achieving a second pass of the pump beam through the crystal. A higher doping level beyond 1 mol% is not an option because it causes increasing scattering losses and decrease of upper level lifetime. A slope efficiency of 76% (optical-to-optical efficiency of approximately 66%) at 1047 nm and 0.8 watt of cw output power was obtained in a small linear cavity containing a 8 mm long Nd:YLF crystal pumped at 880 nm (Lue *et al.*, 2010b). 9.5 W of cw output power in fundamental mode were obtained at 1053 nm with 71% slope efficiency and 63% of optical efficiency with respect to absorbed pump power using a 10 mm long crystal pumped also at 880 nm in a V-shaped cavity using a polarization preserving pump setup (Schulz and Kracht, 2009). In both cases the output power was limited by the available pump power and not by onset of thermal effects. As a last resource, one can combine direct upper laser level pumping with a pump source of excellent beam quality such as a Ti:sapphire laser. This permits the use of long crystals that well absorb the pump power with good pump-to-laser beam overlap. This scheme has been employed in a simple linear cavity by Zhang *et al*. (2011). They achieved a slope efficiency of almost 64%, limited mainly by the short Nd:YLF crystal of only 8 mm. So far the maximum cw output power of commercial Ti:sapphire lasers is about 10 W, posing a limit to the maximum output power that can be achieved using this technique. Additionally, at this output power level, diode pumping is economically much more viable.

12.2.4 Side-pumping of Nd:YLF lasers

High-power diode lasers generally come in the form of a linear array of emitters and are diffraction limited perpendicular to the array and highly multimode in the direction of the array. This makes it very simple to pump lasers laterally with diode bars by placing them along the intracavity beam path inside the gain medium. In this configuration the diode bar generates a thin gain sheet inside the YLF crystal that is passed once or several times by the intracavity fundamental mode in the perpendicular direction. One of the major concerns with side pumping is the pump-to-laser beam overlap, given the relatively low pump absorption of Nd:YLF. It is therefore of interest to have large intracavity fundamental modes. Alternatively, one may reflect the pump beam several times back to the location of the laser mode as in cylindrical pump cavities. A large amount of work has been done on multipass-slab resonators that use a combination of these methods (Dergachev *et al*., 2007). In this setup, a gain crystal of length 28 mm and cross-section 6 mm × 2 mm ($W \times H$) is pumped by two laterally offset fast-axis collimated diode bars. The pump radiation is reflected once from the facet opposite to the pump face and the fundamental beam undergoes five passes through the gain sheet. At up to 64 W of cw pump power the authors obtained 20 W and 30 W of output power at 1053 nm and 1047 nm, corresponding to an optical efficiency of 31% and 43%, respectively (Snell *et al*., 2000). Using the same technology, further improvement was achieved by direct pumping into the upper laser level using a wavelength of 863 nm, resulting in cw multimode operation at 47% optical efficiency and TEM_{00} operation with 37% efficiency at 1047 nm (Pati and Rines, 2009).

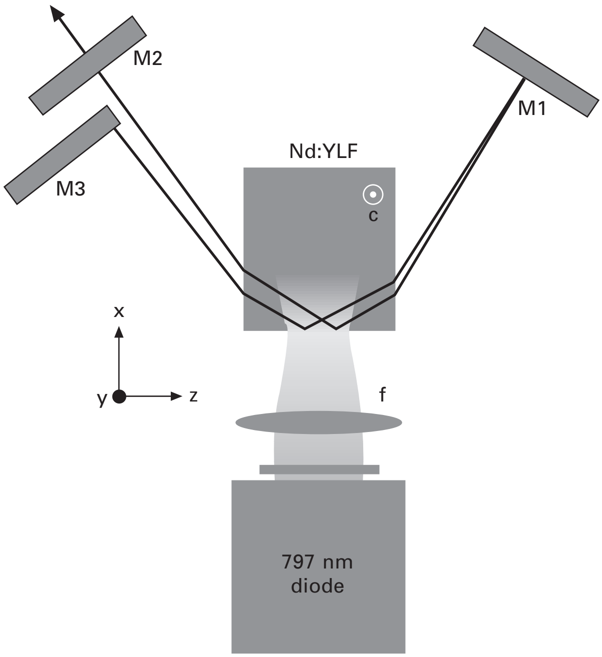
The same group investigated pulsed operation with Nd:YLF in an oscillator–amplifier system that consisted of a single-frequency master oscillator delivering 1 mJ and 10 ns pulses that were subsequently amplified by three pre-amplifiers (using the same design outlined above) and one main amplifier to generate 55 mJ at 1047 nm with 1 kHz repetition rate (Isyanova and Moulton, 2007). Their main amplifier used a diode stack with a total of 285 W of pump power.

An optical-to optical efficiency of 47% in fundamental mode with 16.7 W of the peak output power during quasi-cw operation has been achieved at the wavelength of 1053 nm by a pumping method that can be envisioned as a mix of side- and longitudinal pumping (Wetter *et al*., 2009; Deana and Wetter, 2012). The design makes use of the high inversion density created by π-polarized absorption and located in a shallow region near the pumped surface as with end-pumping and takes advantage of the 1053 nm transition to benefit from the weaker thermal lens. The fundamental mode enters the quadratically shaped slab of 13 mm side-length and 3 mm height at the Brewster angle and undergoes total internal reflection at 56° at the pump facet (see Fig. 12.5). The gain sheet is then double-passed by the fundamental beam in a controlled manner to ensure high beam quality (Wetter *et al*., 2008b).

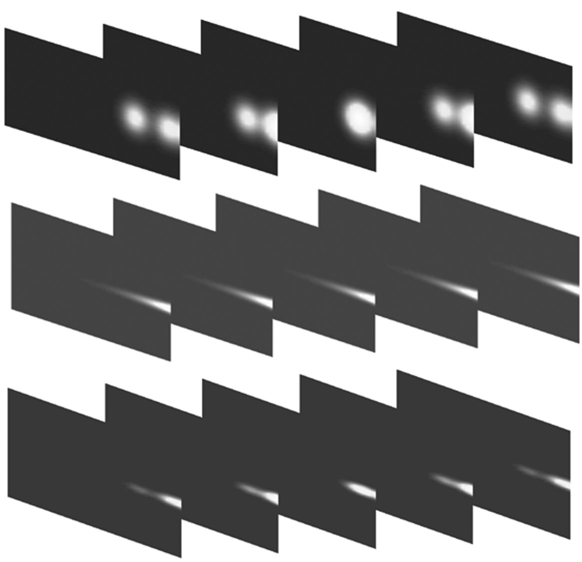
Good efficiency in Q-switched operation has been obtained in a novel setup that used a 3 mm diameter rod cut in half and polished along the optical axis (Pati *et al*., 2008) with a cross-section that is a half-circle. The 792 nm pump wavelength is incident upon the AR-coated cylindrical surface and reflected back by the HR-coated large plane surface which also serves for conduction cooling. Using a Cr:YAG saturable absorber, the authors achieved close to diffraction-limited 7 mJ pulses at 1053 nm with 17% of optical efficiency and less than 10 nanosecond pulses.

A good example of power scalability has been presented by Hirano *et al*. (2000). A conduction-cooled, 78 mm long Nd:YLF rod was embedded in a MgF_2 confinement cavity of approximately triangular cross-section and pumped by 18 five-bar cw stacks with 168 W of average power. The large lateral surfaces of this high thermal conductivity pump chamber were HR coated and served as heat sink whilst the flattened ridges were AR coated for the pump radiation. A total output power of 72 W with an M^2 value of 8 and 43% optical efficiency were measured at 1053 nm.

Lamp-pumped Nd:YLF amplifiers used in laser fusion and high-energy-density experiments have been substituted in many facilities by diode-pumped amplifiers because of the stringent requirements in terms of energy and intensity stability that cannot be met by flashlamps. One such example is the photo-injector of the linear collider nuclear test facility at the European organization for nuclear research (CERN) (Petrarca *et al*., 2011). The photo-injector produces first 8 ps pulses of 6.6 nJ at a repetition rate of 1.5 GHz with 10 W of average power using a commercial Nd:YLF MOPA system. A 400 μs long burst of pulses then gets amplified in two Nd:YLF diode-



(a)



(b)

12.5 (a) Double pass through side-pumped Nd:YLF. (b) Five *xy*-slices of the diode-side-pumped region of the Nd:YLF crystal. Top to bottom: two TEM_{00} modes undergoing total internal reflection at the pump surface; absorbed pump power inside crystal; overlap of the two TEM_{00} modes with the pump inversion (Wetter *et al.*, 2009).

side-pumped amplifier stages with 5 Hz repetition rate (Ross *et al.*, 2003). At pump powers of 15 kW and 17.8 kW in the first and second amplifier stages, the pulses get amplified to 5.5 μJ. Another such system that employs a Nd:YLF amplifier in its front end is the HALNA (High Average power Laser for Nuclear fusion Application) system at Osaka University in Japan (Yasuhara *et al.*, 2008). The diode-pumped Nd:YLF regenerative ring double amplifier system increases the output energy from 13 nJ to 380 mJ in eight round-trips (Sekine *et al.*, 2007).

12.3 Alternative laser transitions

12.3.1 Laser transitions to the ground level

Amongst the most commonly used neodymium doped laser hosts such as YAG, YLF, YVO_4 and $GdVO_4$, the energy of the $^4F_{3/2}$ level is highest for Nd:YLF. Consequently, transitions to the uppermost Stark level of the $^4I_{9/2}$ ground state have the shortest wavelength in Nd:YLF, specifically 908 nm and 903 nm for the σ- and π-transition, respectively. This is of interest for second harmonic generation (SHG) to the deep blue region (Jonas Jakutis *et al.*, 2010). Using direct pumping into the emitting level and a special mirror coating with high transmission at 880 nm and high reflection at 908 nm, 4.7 W of cw output power at 11.8 W of absorbed pump power were achieved (Liang *et al.*, 2011). Given the lower emission cross-section at 903 nm, this emission is much harder to obtain (Spiekermann and Laurell, 2000).

The natural birefringence and the small thermal lens of Nd:YLF are of paramount importance whenever non-linear parametric processes are required, such as SHG or SFG (sum-frequency generation), and have resulted in a strong revival of Nd:YLF as a laser material. By reimaging the 35 W fiber-coupled 880 nm pump beam into a 15 mm long Nd:YLF crystal inside a Z-cavity, 4.3 W of cw blue output power at 454 nm have been obtained using SHG in a 10 mm long LBO crystal (Lue *et al.*, 2010a).

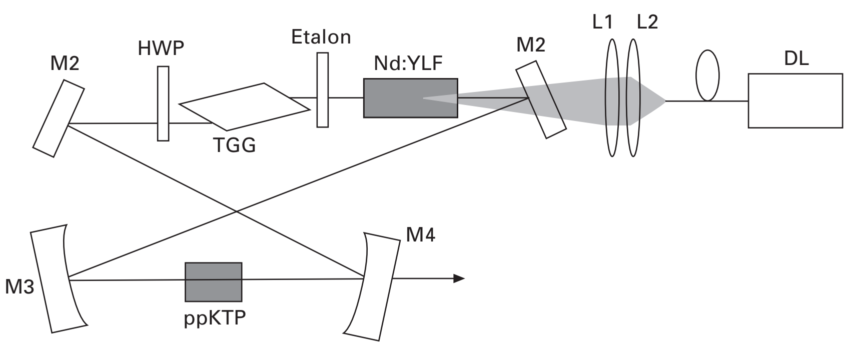
12.3.2 Laser transitions to the $^4I_{13/2}$ energy level

Upon emission into the $^4I_{13/2}$ energy level, Nd:YLF generates two strong lines at 1313 nm (σ-polarization) and 1321 nm (π-polarization). Both lines have been efficiently brought to lasing action in fundamental mode by using direct end-pumping into the emitting level and a crystal whose laser facet opposite to the pump facet was HR coated for the pump wavelength to achieve better pump absorption. An optical efficiency of 49% and 3.6 W of cw output power has been achieved at 1321 nm (Lue *et al.*, 2010c). Using a c-cut 16 mm long crystal, an optical efficiency of 30% with an output power of 3.1 W has been obtained (Li *et al.*, 2011). Both wavelengths can be efficiently frequency doubled into the red spectral region as has been demonstrated using tunable single-frequency ring cavities. More than one watt of single-frequency output power in a diffraction limited mode has been obtained at 657 nm and 660 nm using a periodically poled $KTiOPO_4$ crystal for SHG inside a ring cavity (Zondy *et al.*, 2010; Sarrouf *et al.*, 2007). Pump wavelength was off-center at 806 nm and the doping level of the Nd:YLF crystal was only 0.7 at% to dilute the absorption and keep upconversion low. Unidirectional operation was achieved using a Brewster-cut TGG rod and a zero-order half-wave plate (see Fig. 12.6). Fine tuning of the wavelength was obtained with a thin fused intracavity etalon.

These ring-cavities permit tunable, mode-hop free operation up to the maximum output power because of their absence of spatial hole-burning and are therefore ideally suited for cooling transitions of atomic species in clocks such as silver, calcium and lithium atoms (Camargo *et al.*, 2010).

12.4 Future trends

As has been pointed out in this chapter, almost all major drawbacks of Nd:YLF with respect to other neodymium doped hosts can be overcome if the heat is properly removed. Use of long and thin Nd:YLF rods with low doping levels is a solution but efficient pumping is still limited by incomplete pump overlap or expensive pump sources with low output powers such as Ti:sapphire. Recently a very high pump power of the order of 12 W has been achieved with tapered diodes in a MOPA (Master Oscillator Power Amplifier) configuration at almost diffraction-limited beam quality (Sumpf *et al.*, 2009). If these devices become commercial then this should prove a route to efficient Nd:YLF lasers with output powers achieved so far only



12.6 Single-frequency, tunable ring-cavity for efficient SHG conversion to the red (Camargo *et al.*, 2009). M1–M4 are the ring-cavity mirrors, HWP is the half-wave-plate that together with the TGG makes the optical diode, L1 and L2 are the two doublet lenses that focus the fiber-coupled diode laser (DL) into the Nd:YLF crystal.

by oxide hosts whilst maintaining the excellent beam quality inherent to this material.

12.5 References

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