Chapter 1

State of the art

The initial goal of my thesis was to achieve a high-power red–green–blue (RGB) laser source in the 50 W white light power range for large-screen digital movie projection. High-power RGB is usually achieved by a high-power IR nanosecond [1], picosecond [2], or even femtosecond [3] mode-locked short-pulse laser source followed by a sequence of nonlinear stages including second-harmonic generation (SHG) and sum-frequency mixing (SFM), and an optical parametric oscillator (OPO) [2], or an optical parametric amplifier (OPA) and an optical parametric generator (OPG) [3]. Since such RGB generation stages have proven high conversion efficiencies up to 50% from IR to white light, the main limitation in scaling the power of these sources is the difficulties associated to the design of a high-power IR source. This is often achieved with a master-oscillator power-amplifier (MOPA) configuration, where a low-power pulsed source is amplified in multiple stages to reach $\sim$ 50 W output power. More recently an 80 W thin-disk oscillator was chosen to directly achieve a high output power, yet at the cost of a complex system and limited optical efficiency [3].

Building on the RGB systems previously demonstrated in the group of Prof. Wallenstein, a picosecond mode-locked oscillator delivering from a few watts up to 20 W was assumed, yet the challenge resided in amplifying its output up to $\sim$ 100 W in a minimum number of stages and with a high efficiency. This research led to the development of a specific pump–crystal combination that allowed the realization of high-power oscillators. Thus the initial goal of a high-power amplifier for an RGB source shifted to the design of a broad range of oscillators operated in cw, Q-switched, and mode-locked regimes. Finally a complete mode-locked MOPA delivering 111 W of average output power was constructed, which should allow for the production of $\sim$ 55 W of white light.

Before going into the detail of the systems developed in this thesis, the following sections give an overview of the different technologies that would be candidates for a high-power high beam-quality IR source. Their strengths and weaknesses are outlined to explain the initial review process I conducted at the beginning of my work, and why a well-established technology that was believed to be inherently limited in terms of power scaling was chosen over more modern solutions. Thermal effects being the main limitation in power scaling, technologies fall into two groups: the ones that try to compensate thermal lensing (rods and slabs), and the ones that suppress thermal lensing by design (disks and fibers).

1.1 Rods

1.1.1 End-pumped rods

End-pumped lasers where the pump beam is absorbed in the gain medium colinearly to the laser mode provide a high efficiency and a high beam quality and symmetry thanks to the optimized mode matching. The most common combination in medium-power commercial systems consists in a Nd:YVO_4 crystal pumped by a fiber-coupled diode-laser source. Such system benefits from the high gain and polarized output of vanadate, and from the round homogenized pump profile providing an optimal overlap with a Gaussian mode. Average output powers of $\sim$ 20 W are achievable by end-pumping the crystal from both sides [4]. When higher powers are sought, a periodic resonator comprising two or more crystals can be assembled [5], yet a single or multi-stage MOPA is often simpler and more reliable [6]. Other major advantages of such systems include the mature technologies and widespread know-how associated with the pump source, the crystal, and the resonator. Thus the cost and the availability of reliable components combined to the reduced product development times will facilitate market penetration and customer acceptance.

However the strong thermal lens and the absorption of the largest portion of the pump light close to the input facet of the crystal effectively limits power scalability, so other schemes are chosen when high output powers are sought. Yet recent developments have led to increased output powers with Nd:YAG and Nd:YVO_4 crystals, including direct upper laser-level pumping at 885 nm for YAG [7] and 880 nm for vanadate [8], multi-segmented rods with sections of increasing doping concentration along the length of the crystal for a more homogeneous heat load [9], and even rods with hyperbolic doping where this concentration gradient is directly created during the crystal growth for a continuous variation [10]. Undoped difusion-bonded end-caps have also proven to improve heat-removal and minimize the bulging of end-facets, yet with a limited availability associated to manufacturing difficulties [11]. Cryogenically-cooled Yb:YAG lasers elegantly suppress thermal lensing thanks to the much higher thermal conductivity at cryogenic temperatures, yet such technique is totally unpractical for a commercial laser [12].

1.1.2 Side-pumped rods

Side-pumping of a rod consists in delivering the pump light to the crystal perpendicularly to the laser mode. Thus the crystal's end-faces are not subject to the pump light and power scaling is achieved simply by increasing the crystal length and the number of pump sources surrounding the rod. Some of this technology being inherited from the flash-lamp-pumped lasers, this technique is widely industry-proven.

High output powers > 200 W have been demonstrated along with diffraction-limited beam quality, yet with limited optical efficiencies of $\sim 20\%$ resulting from the necessary underfilling of the pump volume with the laser mode [13]. Most systems integrate Nd:YAG crystals since they can be grown in large boules, so that > 100 mm rods are available. Its favorable thermo-mechanical properties allow for high overall pump power to be applied, yet the strong thermally-induced birefringence effects need to be compensated for achieving a polarized output. Thus it is necessary to insert a polarizing element such as a Brewster plate and compensate for the thermally-induced by integrating for instance two identical laser heads and a quarter-wave plate in the resonator to achieve a stable polarized output. Such oscillator further amplified in a two-head side-pumped stage provided 200 W of IR, which could be efficiently converted to 65 W of third harmonic at 355 nm [6].

1.2 Slabs

Slabs are crystals that exhibit a large aspect ratio between their width and their thickness. For a given crystal cross-section area along the optical axis, the larger the aspect ratio of the slab, the larger the top and bottom surfaces available for cooling. Thus a slab will allow a very efficient unidirectionnal heat extraction perpendicularly to these surfaces. However this leads to a unidirectionnal thermal lens that is more difficultly compensated than a symmetric lens. The gain volume is also strongly assymetric so that achieving a good overlap with a near diffraction-limited mode is not straightforward. One solution consists in multipassing a small round mode to cover the whole width of the slab, yet this solution is better implemented in low thermal lens materials such as Nd:YLF [14]. Another technique is to design a stable/unstable resonator, the cavity being stable in the direction of cooling and unstable along the slab width [15, 16]. The output coupling is then achieved with a cut end-mirror, with the downside of diffraction on the mirror edge resulting in side-lobes on the beam. Cleaner beam profies can be achieved by extracavity spatial filtering, yet at the cost of some power loss.

1.2.1 End-pumped slabs

Similarly to a rod, a slab can be end or side-pumped. End-pumping offers a homogeneous pump profile and its optimal matching to the laser mode without wasting pump power that is not accessible to the laser mode on the crystal edges as with side-pumping. The pump beam achieved by combining the output of several diodes in high-power systems should however be homogenized to minimize distortions on the laser mode. The main power limitation results from the input facet which is subject to the totality of the pump power, yet the spreading of the pump beam on a wide crystal makes this limitation much less restrictive than in regular end-pumped rods. End-pumped Nd:YVO$_4$ slab oscillators with output powers > 100 W have been demonstrated [15], combining the benefits of a high-gain material, the power-handling capability of a slab design, and the short length of a stable–unstable resonator. These favorable parameters allow for the production of short (< 10 ns) pulses with high average powers, which would be difficult to obtain with an end-pumped rod in a stable resonator.

1.2.2 Side-pumped slabs

Side pumping allows for the extension of the slab length and of the number of pump diodes for power scaling. However, the pump volume cross-section is inhomogeneous, with the crystal edges pumped to the highest level being left undepleted. A Nd:YAG thin-slab stable–unstable resonator provided 220 W in Q-switched operation with a near diffraction-limited beam quality ($M^2 = 1.5$) [16]. Very compact Nd:YLF and Nd:YVO$_4$ side-pumped slab modules in which the symmetric laser mode follows multiple passes to cover the whole crystal width have been operated as oscillators or in multi-stage power-amplifier systems [14].

Grazing-incidence slabs consist in bouncing the laser mode off the crystal's side-pumped facet by total internal reflection at a very shallow angle. When pumping with one diode bar collimated on its fast axis for instance, the absorption can be made very high and the pump beam focused on a thin line since the pump light is spread on the whole width of the diode bar. The laser mode travels through a very small cross-section gain area, providing extremely high gain for the production of short Q-switched pulses at high repetition-rates > 500 kHz in a vanadate slab [17].

1.3 Disks

While thermal lensing is inevitable in rods and slabs for which the resonator design is critical for minimizing its effects, disks and fibers are inherently free from thermal lensing effects. A disk laser consists in a thin crystal in which the unidirectional heat flow resulting from pump absorption and cooling follows the same direction as the laser mode [18]. Thus the thermal gradient existing only on the laser mode axis, and not perpendicularly in the beam cross-section, no thermal lensing is created by the heat flow. Although a disk may be side or end-pumped, the most effective design for small-mode high beam-quality sources resides in end-pumping. This is achieved by coating a thin ($< 300\mu$m thick) crystal with a HR coating on the back side and an AR coating on the front side, both for the pump and laser wavelengths. The disk is then cooled from a back side by soldering the crystal on a heat-sink, and pumped from the front side on a spot ranging from ~ 1 mm for medium-power systems to > 1 cm for high-power lasers. Since the double-pass pump absorption is very low because of the small crystal thickness, a large number of passes (up 16 or even 32) is necessary to achieve an efficient absorption. Thus a complex pump multi-passing cell integrating a parabolic mirror and roof prisms is required.

High average powers have been demonstrated with diffraction-limited beam quality, with 83 W in a mode-locked Yb:YAG oscillator producing 800 fs pulses, yet with a repetition-rate limited by the relatively low gain resulting from the large mode size, and an optical–to–optical efficiency under 25% [19, 3]. Scaling the power of thin-disk systems requires to enlarge the pump spot and mode size, achieving > 2 kW per disk, yet with a deteriorated beam quality of $M^2 > 5$ [20]. The degradation in beam quality arises from the thermally-induced mechanical deformation of the thin disk, which is all the more significant at high pump powers and when the laser mode is enlarged to cover a large area on the disk. Yet diffraction-limited output-beam quality is commercially available in cw, Q-switched [21], and mode-locked operation regimes [22] in the 50–100 W output power range.

More recently much progress has been made on optically-pumped semiconductor lasers (OPSL), where a semiconductor disk containing a thin active layer a Bragg reflector is optically end-pumped. Multiple-disk resonators have been demonstrated, achieving noise-free intracavity second-harmonic generation with > 50 W at 532 nm [23].

1.4 Fibers

Fiber lasers and amplifiers rely on a glass active fiber integrated a doped core as the gain medium. Since wave-guiding is achieved in a step-index or even a photonic-crystal structure, the temperature rise and thermal gradients have in principle no effect on the mode propagation. A double-clad architecture combining the benefits of a small single-mode core and large pump core allow for the efficient coupling of a low-quality diode pump beam, yet retaining the diffraction-limited mode quality inherent to a single-mode core. High cw output powers $> 1kW$ with diffraction-limted beam quality have been demonstrated in such configuration, yet high-power short-pulse lasers are limited by the nonlinear effects in a small core and long fiber, and ultimately by the damage threshold of the fiber's facets.

When high-power pulsed operation is sought, a large-mode-area (LMA) fiber where the core is enlarged to a diameter $> 50\mu$m allows for the strong reduction of the mode power density, the increase of the laser-core to pump-core ratio and therefore the reduction of the fiber length while maintaining a high pump absorption. These combined improvements allow for much higher pulse energies and shorter pulses to be achieved before excessive nonlinear effects or fiber facet damage occur. Thus oscillator fiber-amplifier systems have demonstrated high-power operation with high beam quality in the nanosecond regime with 60 W of second harmonic [24], and in the picosecond regime with 80 W of green 530 nm radiation [25].

Even larger core diameters in the $50 - 100\mu$m range are achieved in rod-type fibers, where a photonic-crystal structure allows for the guiding of a single mode on a larger area than in a regular step-index fiber [26]. Such fiber being very sensitive to bending losses, its > 1 mm outer diameter provides the necessary stiffness and cooling area for removing the heat of fibers that are typically very short (< 1 m).

1.5 Concept comparison

None of the technologies briefly presented in this chapter is the ideal solution to all high-power requirements, yet their main strengths and weaknesses can be outlined to help selecting one or another for a given need in terms of cw or pulsed operation, pulse duration and repetition-rate, polarized emission, efficiency, and beam quality. Table 1.1 summarizes the potential of each technology for the main parameters characterizing the laser emission. Since this table is very synthetic, it gives a general trend for each technology group, although some specific arrangements, such as grazing-incidence slabs or rod-type fiber lasers may present different behaviors.

After a complete technology round-up, end-pumped vanadate appears to be the most versatile and all-round performing configuration, yet it is strongly limited in terms of average output power. Other technologies benefiting from much more promising power-scaling potential each suffers from its own weaknesses, wether in cw or pulsed operation, or simply in terms of simplicity, ease of manufacturing, or know-how establishment. This technology comparison and knowing the simplicity and versatility of end-pumped vanadate systems convinced me it was worth trying to push the average output power limits of this well-established technology, even if it didn't reach the same power levels as some more recent yet less versatile and more complex technologies. This is the subject of the work presented in this thesis.

Table 1.1: Comparison of the performance of high-power laser technologies for each determining laser output parameter. Systems refer to respectively end-pumped Nd:YVO_4 rods, side-pumped Nd:YAG rods, end-pumped Nd:YVO_4 slabs, side-pumped Nd:YAG slabs, Yb:YAG disks, and Yb-doped double-clad fiber lasers.

	Rod		Slab		Disk	Fiber
	End	Side	End	Side		
Average output power	−	+	+	+	+	+
Beam quality	+	−	−	−	+	+
Efficiency	+	−	+	+	−	+
Polarized output	+	−	+	−	+	−
Q-switching easiness	+	+	+	+	−	−
Short ns pulses	+	−	+	−	−	−
High repetition rate	+	−	+	+	−	−
Mode-locking easiness	+	−			+	−
Repetition rate	+	−			−	−
System simplicity	+	+	+	+	−	−