Thin Disk Lasers

Power scalability and beam quality

The results for cw- and q-switched operation as well as for the amplification of short (ns) and ultra-short (ps, fs) pulses demonstrate the potential of the thin disk laser design. The scaling laws for this laser design show that the power limit for cw-operation is far beyond 10 kW for a single disk and the energy limit is higher than 1 J from one disk in pulsed operation. Due to the surface cooling of the disk, the optical distortion of the laser beam is low and therefore operation of the thin disk laser is possible in fundamental mode at extremely high output power.

The thin disk laser concept is a laser design for diode-pumped solid-state lasers, which allows the realization of lasers with high output power, having very good efficiency and also excellent beam quality. Since the first demonstration of the principle in 1993 the output power of one single disk has been increased to 4 kW in cw-operation. Thin disk lasers with up to 4 kW are now commercially available for materials processing. The beam quality (focusability) of all commercially available thin disk lasers is always better than for rod lasers of similar power. Furthermore, lasers with up to 100 W of power are available with fundamental mode ($M^2 < 1.2$). Additionally, the electrical efficiency is higher than that of all other commercially available solid-state lasers with similar power.

The thin disk laser design also allows highly efficient pulsed operation as a q-switched laser or as a laser amplifier. In particular, the generation and amplification of ultra-short pulses is possible with a very high average power and also high efficiency. These properties of thin disk lasers will open the way to a completely new class of ultra-short pulsed laser systems for materials processing.

With all its outstanding features, the thin disk laser will not only replace classical laser systems in many applications but in particular it will create new markets for laser technology which need the specific properties of thin disk lasers which cannot be provided by classical laser systems.

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Thin disk laser principle

One of the outstanding features of the thin disk laser is its excellent beam quality, which results from the surface cooling of the laser disk. Figure 1 shows the principle of the thin disk laser design [1, 2]. The laser crystal is shaped as a disk with a diameter of several mm (depending on the output power/energy) and a thickness of 100 µm to 200 µm, depending on the laser active material, the doping concentration and the pump design. The disk is highly reflective coated on its back side for both the laser and the pump wavelengths and anti-reflectively coated on the front side for both wavelengths. This disk is mounted with its back side on a water-cooled heat sink using indium-based or gold-tin solder. This technique allows a very stiff fixation of the disk on the heat sink without any deformation of the disk, which acts as a mirror. To reduce the

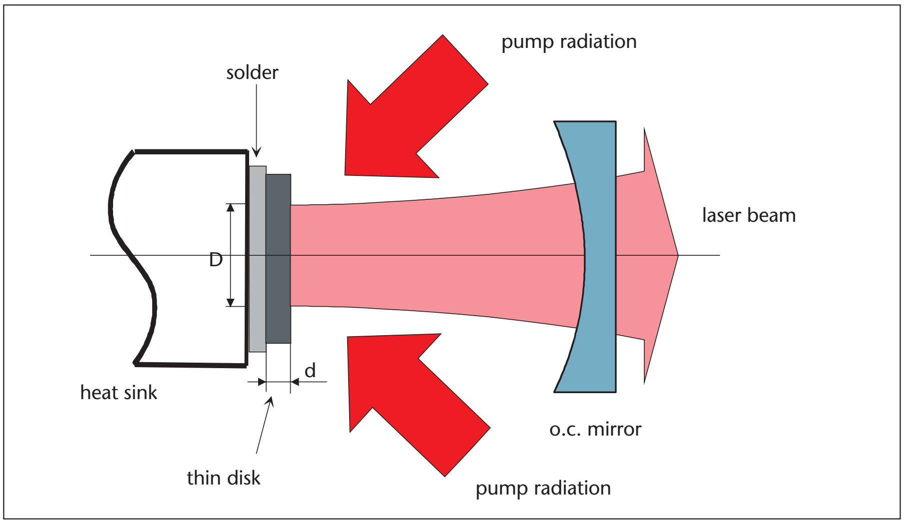

FIGURE 1: **Thin disk laser design: The laser crystal is shaped as a disk with a diameter of several mm (depending on the output power/energy) and a thickness of 100 µm to 200 µm.**

stress during the soldering process, as much as possible, the heat sink is made from a heat expansion matched material (Cu-W). The heat sink is water-cooled by impingement cooling using a multi-nozzle design inside the heat sink.

Due to this mounting and cooling technique, the temperature gradients inside the laser crystal are mainly coaxial to the disk axis and the laser beam axis. The temperature in the radial direction is nearly uniform within the homogeneously pumped central area of the disk. Therefore, these temperature gradients only slightly influence the laser beam propagation through the disk. All the thermal lens effects and the aspherical parts of the profile of the index of refraction are reduced by more than one order of magnitude compared with rod laser systems. The stress-induced birefringence is even further reduced and can be neglected for real laser systems. Additionally, due to the large surface-to-volume ratio, the heat dissipation from the disk into the heat sink is very efficient, thus allowing operation at extremely high volume power densities in the disk (up to 1 MW/cm³ absorbed pump power density).

The crystal can be pumped in a quasi-end-pumped scheme. In this case the pump beam impinges on the crystal at an oblique angle. Depending on the thickness and the doping level of the crystal, only a small fraction of the pump radiation is absorbed in the laser disk. Most of the incident pump power leaves the crystal after being reflected at the back side. The absorption can be increased by successive re-directing and imaging of this part of the pump power onto the laser disk. A very elegant way of increasing the number of pump beam passes through the disk is shown in Figure 2. The radiation of the laser diodes for pumping the disk is first homogenized either by fibre coupling of the pump radiation or by focusing the pump radiation into a quartz rod. The end of either the fibre or the quartz rod is the source of the pump radiation, which is imaged onto the disk using the collimating lens and the parabolic mirror. In this way a very homogeneous pump profile with the appropriate power density in the disk can be achieved, which is necessary for good beam quality. The unabsorbed part of the pump radiation is collimated again at the opposite side of the parabolic mirror. This beam is re-directed, using two mirrors, to another part of the parabolic mirror where the pump beam is focused again onto the disk, this time from another direction. This re-imaging procedure can be repeated until all the (virtual) positions of the parabolic mirror have been used. At the end the pump beam is re-directed back to the source, thereby doubling the number of pump beam passes through the disk. In this way up to 32 passes of the pump radiation through the disk have been realized and more than 90% of the pump power is absorbed into the disk.

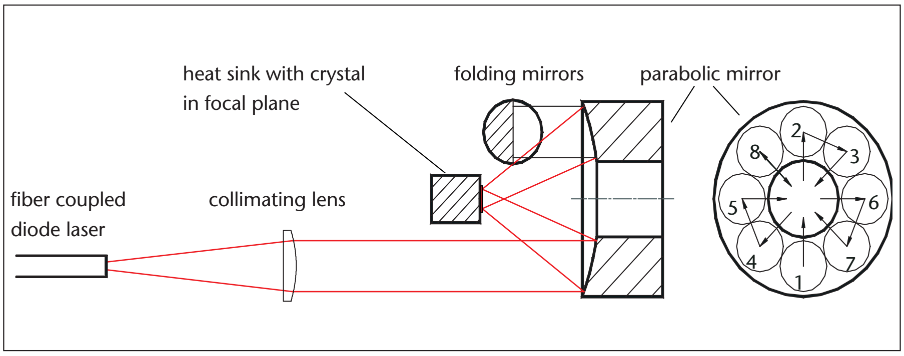

FIGURE 2: **Pump design of the thin disk laser with 16 pump beam passes. The radiation of the laser diodes for pumping the disk is first homogenized either by fibre coupling of the pump radiation or by focusing the pump radiation into a quartz rod.**

Using multiple pump beam passes through the disk, results in a thinner disk and/or a lower doping concentration, thus reducing the thermal effects such as thermal lensing and stress in the disk. Another advantage is that the effective pump power density is increased (nearly 10 times for 16 pump beam passes) so that on the one hand the demands to the power density (beam quality) of the pump diodes are reduced and on the other hand, quasi-three-level laser materials (e.g. Ytterbium-doped) can also be used with this design.

Quasi-three-level materials offer, on one hand, the possibility of building lasers of the highest efficiency. But on the other hand, they are hard to operate because they show a relatively high absorption of the laser-wavelength since the lower laser level is so close to the ground state that a considerable number of the laser-ions are in the lower laser level, when the laser is operated at room temperature. Therefore, it is necessary to pump the material with high pump power density in order to reach the threshold without increasing the temperature of the crystal too much. Using multiple pump beam passes through the crystal is therefore the key to achieve low threshold and high efficiency, because this helps to simultaneously reduce the thickness of the crystal and the doping concentration. This decoupling of laser and pump beam absorption is essential for the operation of quasi-three-level systems. The limit for the possible number of pump beam passes through the disk is given by the beam quality of the laser diodes which determines the beam diameter on the parabolic mirror and hence the number of positions on the mirror which can be used. The better the beam quality of the pump laser diodes, the higher the number of pump beam passes that are possible and the higher will be the total efficiency of the thin disk laser.

When operating the disk in this set-up it is easy to scale the output power or energy just by increasing the pump spot diameter while keeping the pump power density constant. Also, there is no need to increase the brightness of the pump laser diodes.

Besides quasi-three-level systems like Ytterbium and Thulium [3, 4] doped materials (lasing wavelength around 2 µm) nearly all classical laser materials can be operated in the thin disk design, especially if the absorption of the pump radiation is quite high. This has been demonstrated using Nd in YAG [5, 6] and Vanadate hosts.

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The Institut für Strahlwerkzeuge (IFSW) at the University of Stuttgart, founded in 1986, is recognized as one of the leading laser centers worldwide. It´s strength is based on the holistic approach that comprises beam sources as well as their applications and extends from research on the fundamentals to industrial implementation. The strong cooperation with the associated companies of FGSW and TGSW complements the operational instruments through non-commercial research and technology transfer as well as industrial projects. More information under: www.ifsw.uni-stuttgart.de

Continuous-wave operation

Very high laser output power can be achieved from one single disk by increasing the pump spot diameter while keeping the pump power density constant. Figure 3 shows this scaling law for a pump power level up to 1.1 kW. The slope efficiency and the optical efficiency are nearly independent of the pump spot diameter. Up to the present time, nearly 4 kW power has been demonstrated from one single disk. The high efficiency of the thin disk laser results also in a very high electrical efficiency of the total laser system which is higher than 25% for industrial lasers with 1 kW output power and a beam propagation factor M^2 of less than 20.

An alternative way of scaling the output power is the use of several disks in one resonator. More than 6.5 kW laser power has been demonstrated so far using two and four disks in one resonator. Due to the small thermal effects in the disks, the beam quality is nearly independent of the power and is at least three times better (for commercially available thin disk lasers) than that of rod lasers with the same output power.

Depending on the demands from materials processing, the high-power thin disk lasers in the kW power range are operated with a beam propagation factor (beam quality) M^2 of about 20 which means that the focusability of the laser beam is 20 times worse than the theoretical limit ($M^2 = 1$). But beyond this beam quality, the thin disk laser design offers the possibility of also operating high-power lasers in the fundamental mode ($M^2 = 1$) due to the small thermal effects and the small optical distortions in the disk. Using an appropriate resonator design it is possible to achieve high laser output power with high optical efficiency. Figure 4 shows the result of such a disk operating with more than 180 W laser power and an M^2 of better than 1.1. The optical efficiency of this laser was higher than 50%.

Pulsed operation

Besides the outstanding properties of the thin disk laser design for cw-operation it is also well suited for pulsed laser systems, especially if high average output power is required. Up to the present time, pulsed thin disk laser systems have been developed and demonstrated for the ns-, ps- and fs-pulse duration regime. All systems show an excellent beam quality and high efficiency.

Q-switched operation could be achieved by inserting an AOM (acousto-optic modulator) inside the laser resonator. With 140 W pump power 18 mJ output energy has been demonstrated at 1 kHz repetition rate and 6 mJ at 10 kHz repetition rate.

Using the concept of a master oscillator, followed by a regenerative amplifier allows for pulse amplification of ns-, ps- and fs pulses, the oscillator generates pulses with the desired properties (pulse duration, wavelength and repetition rate) which are amplified to the desired energy in the thin disk amplifier. The thin disk amplifier in this scheme is operating independently of the seed laser and is able to amplify any incoming pulse with the right wavelength and a pulse duration which is shorter than the round-trip time of the amplifier resonator.

For a pulse duration of between 5 and 40 ns, so far 37 mJ have been achieved (1 kHz repetition rate, single frequency operation, $M^2 <$ 1.3). Using a ps oscillator (pulse duration 1.8 ps) the amplification of ps pulses up to 5 mJ energy at 1 kHz repetition rate and 1.3 mJ at 20 kHz have been demonstrated. With Yb-doped KYW as the laser active medium, the amplification of fs-pulses could be realized. Up to 160 µJ of energy could be demonstrated with a pulse duration of less than 900 fs and even with a pulse duration of less than 300 fs, more than 20 µJ could be achieved.

Power/Energy scalability and beam quality

Simulations show that scaling of the output power of one single disk is only limited by amplified spontaneous emission (ASE) if the pump spot diameter becomes increasingly larger [7–9]. Fortunately, the gain of low doped Yb:YAG is rather small so that ASE will occur only at very high pump power levels. For a 9 at.% doped disk with a thickness of 200 µm the power limit occurs at a pumping power beyond 50 kW so that much more than 20 kW laser power can be extracted in cw-operation from one disk.

This power level (20 kW) can be considerably further increased by increasing the pump spot diameter. The limitation set by ASE can then be overcome by using a disk with an undoped cap on top of the original disk, thus reducing the mean radial gain by the square of the ratio between the undoped and the doped material.

The simulations also show that the laser power level for fundamental mode operation can be increased to nearly the same power level as for multi-mode operation. The reason for this behaviour is that the aspherical part of the residual thermal lens of the disk

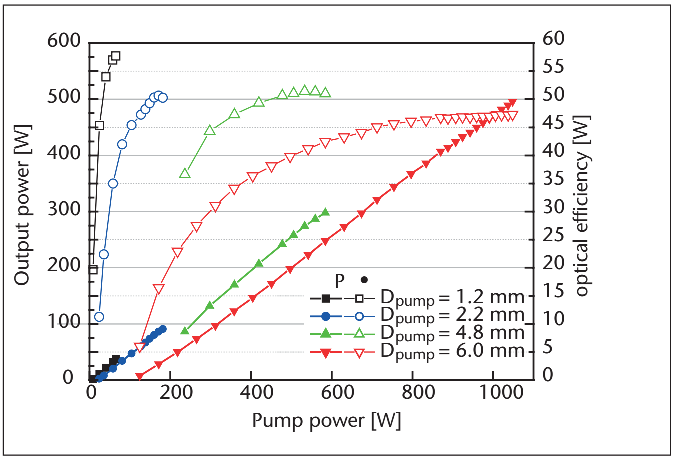

FIGURE 3: **Very high laser output power can be achieved from one single disk by increasing the pump spot diameter while keeping the pump power density constant. Laser results for different pump spot diameters (Yb:YAG, doping 9 at.%, 16 pump beam passes).**

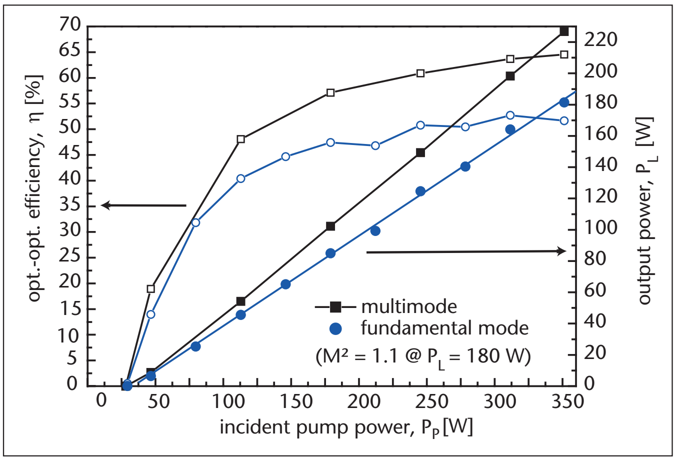

FIGURE 4: **Using an appropriate resonator design it is possible to achieve high laser output power with high optical efficiency. Output power and optical efficiency for multi-mode and fundamental mode operation.**

inside a top-hat pump profile is extremely low (less than 10 nm optical path difference) and independent of the pump spot diameter itself. The additional phase step at the edge of the pump profile is low and also nearly independent of the pump spot diameter. This phase step can be compensated for, by using simple adaptive optics.

Scaling the pulse-energy of one single disk is more strongly limited by ASE than the power under cw-operation since the gain under low repetition rate pulsed conditions is much higher compared with the cw-operation of a disk. Nevertheless, using an undoped cap on top of the disk will result in achievable energy levels far beyond 10 J from only one single disk. This energy can be further increased by using multiple disks in one resonator.

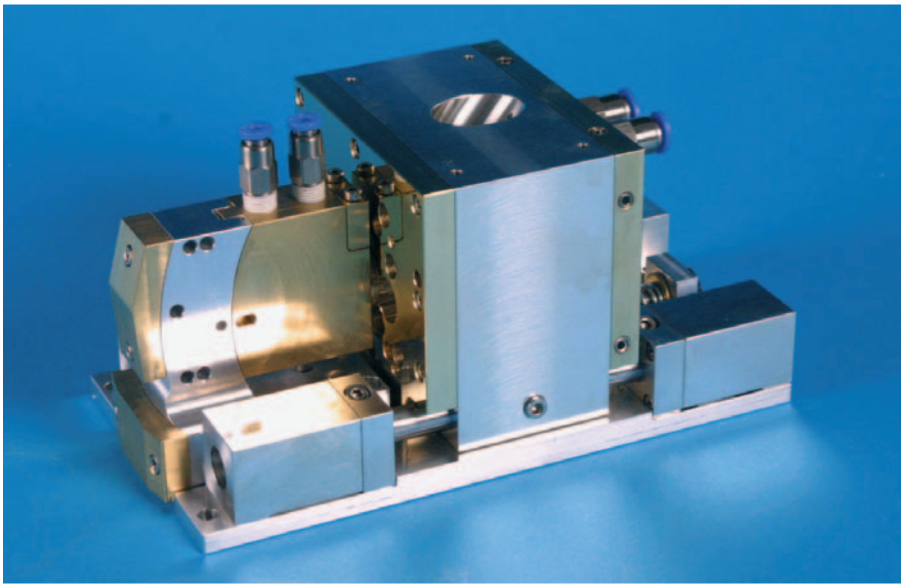

FIGURE 5: **Until the present time, several companies have already been offering thin disk lasers on the market for different applications within materials processing: e.g. a thin disk laser module for up to 500 W Laser power. (courtesy of TGSW, Stuttgart)**

Summary

The thin disk laser is an innovative laser concept that allows one to build diode pumped solid state lasers with the highest output powers, the highest efficiency and the best beam quality, simultaneously. Nearly all operational modes of solid state lasers such as continuous wave, pulsed operation with pulse durations of between femtoseconds and nanoseconds and laser amplifiers, can be built using this design and having better properties than other designs.

Until the present time, several companies have already been offering thin disk lasers on the market for different applications within materials processing. These lasers cover the power range from several watts up to several kW. Figure 5 shows a thin disk laser module which is able to deliver 500 W laser power (the size of the module is 150 x 80 x 80 mm³, courtesy of TGSW, Stuttgart).

In future, new materials will be investigated with the goal of increasing the power, the energy and the beam quality further. Laser output powers of much more than 10 kW and energies of more than several J will be possible. New materials will open new markets for new wavelengths and with semiconductor thin disk lasers, customized lasers for specific markets will become feasible.

Using thin disk lasers for materials processing will considerably increase the process efficiency for many applications. Due to the good beam quality of thin disk lasers deep penetration welding also becomes possible for thin materials as well as remote welding at high power. In summary, the increase of laser and process efficiency will result in substantial cost reduction in laser manufacturing.

Acknowledgments

My special thanks go to some 20 scientists, the technicians and numerous students who have worked on the thin disk laser design since 1992, making the results possible, which are summarized in this paper. Without their enormous commitment these results would not have been possible. Most of the work on thin disk lasers has been funded and strongly supported by the German Federal Ministry of Education and Research, some of the work has also been supported by the state government and by the EU. Various German laser companies have also generously supported thin disk laser development over the last decade.

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