Results and scaling laws of thin disk lasers

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ABSTRACT

The principle ideas of the thin disk laser design will be illustrated and the advantages for operating different laser materials will be explained. The results for cw- and q-switched operation as well as for 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 one single disk and the energy limit is higher than 1 J from one disk in pulsed operation. Also the applicability of the thin disk laser concept to optically pumped semiconductor structures will be discussed. When pumping directly into the quantum wells the energy defect between pump- and laser photon can be smaller than 5% thus reducing the waste heat generated inside the semiconductor structure. First results demonstrate the potential of this new concept. Finally, a short overview of the industrial realization of the thin disk laser technology will be given.

Keywords: solid-state laser, thin disk laser, ultra-short pulse amplification, high-power laser,

1. INTRODUCTION

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, highest efficiency and good beam quality, simultaneously. Since the first demonstration of the principle in 1993 the output power of one single disk could be increased to more than 2 kW in cw-operation. Using four disks in one resonator allows an output power extraction of more than 4 kW. Thin disk lasers with up to 4 kW are commercially available for materials processing. The beam quality (focusability) of all commercially available thin disk lasers is always better than for rod lasers with similar power. Furthermore, lasers with up to 100 W 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 allows also highly efficient pulsed operation as q-switched laser or as laser amplifier. Especially the generation and the amplification of ultra-short pulses is possible with very high average power and 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 thin disk lasers will not only replace classical laser systems in many applications but also and particularly they will open new markets for the laser technology which need the specific properties of thin disk lasers which can not be fulfilled by classical laser systems.

2. THIN DISK LASER PRINCIPLE

One of the outstanding features of the thin disk laser is its excellent beam quality which results from the face cooling of the laser disk. Figure 1 shows the principle of the thin disk laser design[1 - 4]. 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-reflective coated on the front side for both wavelengths. This disk is mounted with its back-side on a water-cooled heat sink using indium-tin or gold-tin solder. This technique allows a

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very stiff fixation of the disk on the heat sink without deformation of the disk which acts as a backside-mirror. To reduce the 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 7 nozzles inside the heat sink.

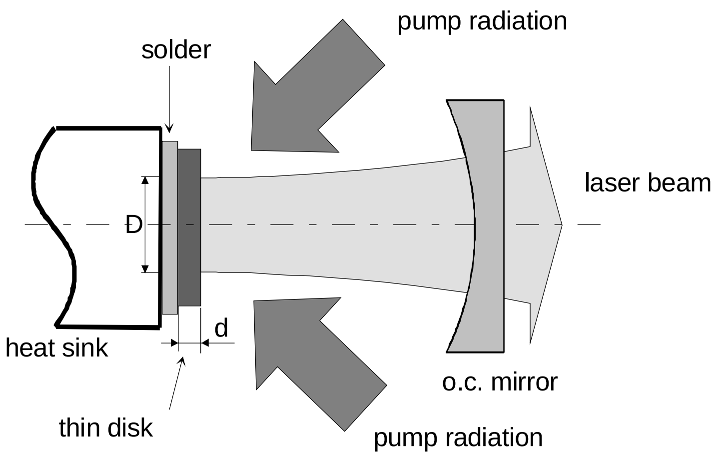

Fig. 1. Thin disk laser design

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 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 aspherical parts of the profile of the index of refraction are reduced by more than one order of magnitude compared to rod laser systems. The stress induced birefringence is even more 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 the operation at extremely high volume power densities in the disk (up to 1 MW/cm^3 absorbed pump power density).

The crystal can be pumped in a quasi-end-pumped scheme. In this case the pump beam hits the crystal under 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. By successive re-directing and imaging of this part of the pump power again onto the laser disk the absorption can be increased. A very elegant way to increase 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 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 in the disk.

Using multiple pump beam passes through the disk results in a thinner disk and/or a lower doping concentration thus reducing the thermal effects like thermal lensing und 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 also quasi-three-level laser materials (e.g. Ytterbium doped) can be used with this design.

Quasi-three-level materials offer on the one hand the possibility to build lasers with highest efficiency. But on the other hand, they are hard to operate because they show a relatively high absorption on the laser-wavelength since the lower laser level is so close to the ground state that a considerable part of the laser-ions are in the lower laser level if the laser is operated at room temperature. Therefore, it is necessary to pump the material with high pump power density for reaching 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 reduce the thickness of the crystal and the doping concentration, simultaneously. This decoupling of laser and pump beam absorption is essential for operating 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 the pump beam passes can be and the higher the total efficiency of the thin disk laser will be.

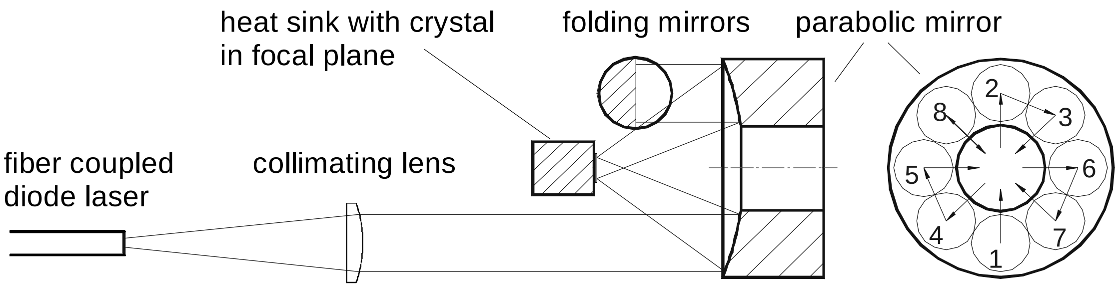

Fig. 2. Pump design of the thin disk laser with 16 pump beam passes

When operating the disk in this set-up it is easy to scale the output power just by increasing the pump spot diameter 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[5,6] (lasing wavelength around 2 µm) doped materials nearly all classical laser materials can be operated in the thin disk design especially if the absorption of the pump radiation is rather high. This has been demonstrated using Nd in YAG[7,8] and Vanadate hosts.

3. THIN DISK LASER IN CONTINUOUS-WAVE OPERATION

Very high laser output power can be achieved from one single disk[9,10] by increasing the pump spot diameter while keeping the pump power density constant. Figure 3 shows the laser results (power and optical efficiency) from an Yb:YAG disk which has been pumped up to the same level of pump power density (about 4 kW/cm²) but with different pump spot diameters between 1.2 mm and 6 mm. It is obvious that the slope efficiency and the optical efficiency curves are similar. But it is also clear that the laser threshold is increased with increased pump spot diameter in fact the threshold is proportional to the pumped area (or better: proportional to the number of laser ions). These measurements demonstrate clearly the power scaling capability of the thin disk laser design.

Figure 4 shows to our knowledge the highest output power from one disk (Trumpf Laser). More than 2 kW power have been achieved with a maximum optical efficiency of 64%. This 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 M² of less than 20.

An alternative way to scale the output power is the use of several disks in one resonator. Figure 5 shows the design of a 4 kW Laser (Trumpf Laser) where 4 disks are coupled together in one resonator and Figure 6 shows the output power of such a laser as function of the pump power and for different numbers of disks used in the resonator. Again, all slope efficiencies are similar but the laser threshold is proportional to pumped area (number of disks). Due to the small thermal effects in the disks the beam quality is nearly independent of the power and is at least 3 times better than that of commercially available rod lasers with the same output power.

Simulations show[11-13] that scaling of the output power of one single disk is only limited by amplified spontaneous emission (ASE) if the pump spot diameter becomes larger and larger. 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 of more than 50 kW so that much more than 10 kW laser power can be extracted in cw-operation from one disk.

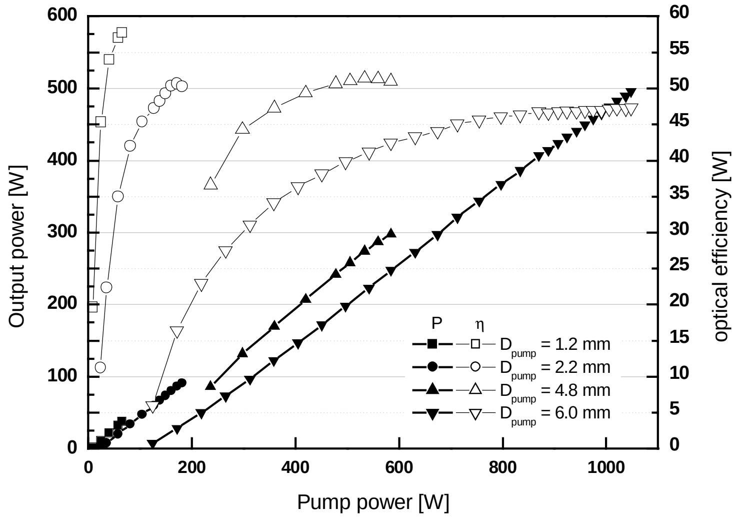

Fig. 3. Laser results for different pump spot diameters (Yb:YAG, doping 9 at.%, 16 pump beam passes)

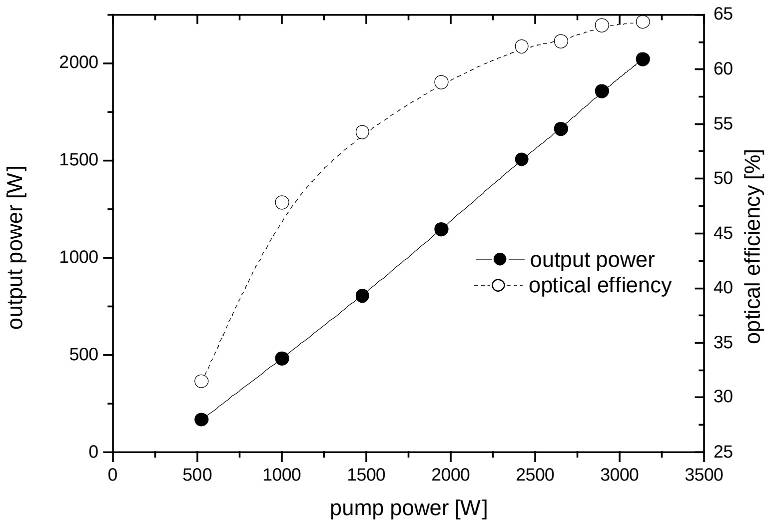

Fig. 4. Output power and optical efficiency from one single disk (courtesy of Trumpf-Laser)

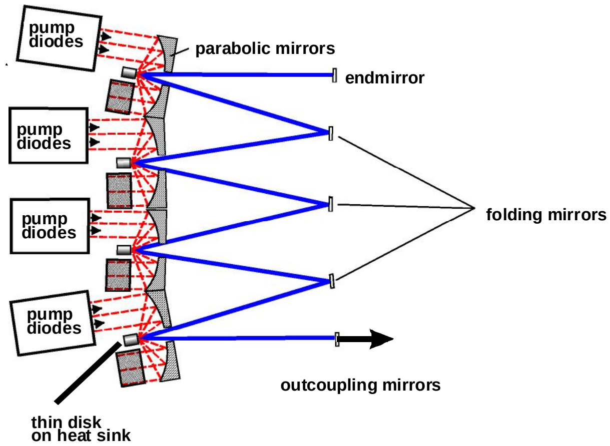

Fig. 5. Design of the 4 kW thin disk laser using 4 disks (courtesy of Trumpf-Laser)

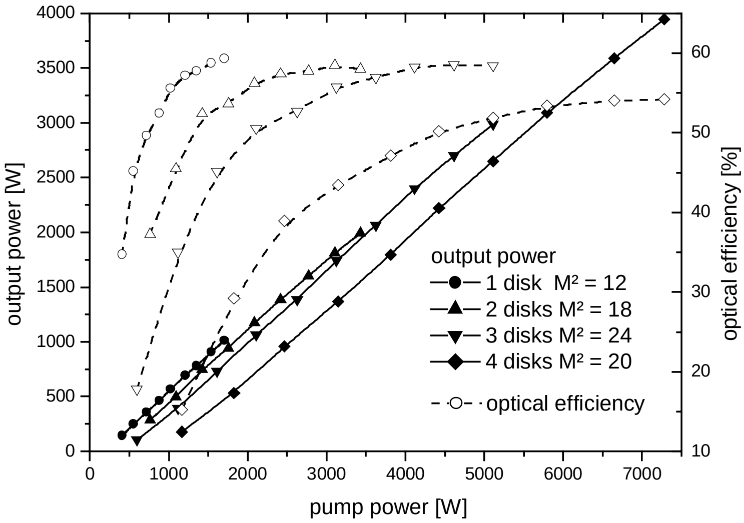

Fig. 6. Output characteristics of the 4 kW laser (courtesy of Trumpf-Laser)

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 that means that the focusability of the laser beam is 20 times worse compared to the theoretical limit ($M^2 = 1$). But beyond this beam quality, the thin disk laser design offers the possibility to operate high power lasers also in the fundamental mode ($M^2 = 1$)[14,15] 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 7 shows the result of such a disk operated with more than 100 W laser power and an M^2 of better than 1.2. The optical efficiency of this laser was higher than 45%. Even higher laser power levels with nearly fundamental mode properties will be possible in future.

With the potential of very high output power levels for the fundamental mode it will be possible to operate thin disk lasers also in single frequency operation[16]. For achieving this, it is necessary to use a birefringent filter and one or two uncoated etalons inside the fundamental mode resonator. With such resonators, up to 30 W single frequency power has been demonstrated. Additionally, the wavelength of the laser can be tuned over a wide spectral range (1000 nm to 1060 nm for Yb:YAG) by tuning the birefringent filter[17-19].

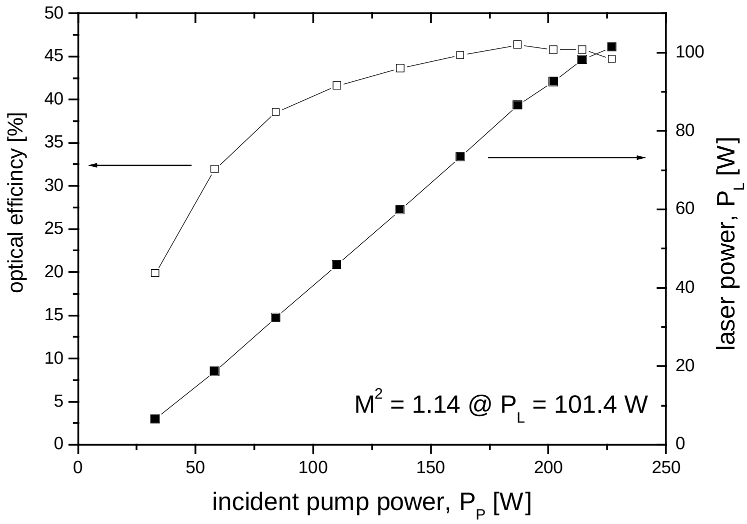

Fig. 7. Output power and optical efficiency for fundamental mode operation

Another interesting feature is resonator-internal doubling of the laser frequency for covering the visible spectral range with high efficiency. This could be demonstrated successfully with different laser materials: With Yb:YAG 15 W green output power (wavelength tunable between 500nm and 530 nm, maximum power around 515 nm) could be shown. For Nd:YVO_4 [20,21] more than 12 W could be demonstrated at 532 nm wavelength and more than 1 W at 457 nm (doubling of the quasi three level transition at 914 nm[22]). For Nd:YAG more than 1 W at 660 nm could be achieved when doubling the 1320 nm transition.

All these results show the potential of the thin disk laser design for high power lasers which are easy to build and to operate. Especially the simple scaling laws of the thin disk laser design and the easy adaptation to many laser active materials will support the implementation of the thin disk laser design to industrial available laser systems.

4. THIN DISK LASER IN 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 demanded. Till today, 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 a high efficiency.

In close collaboration with Ursula Keller´s group at the ETH Zurich high average power fs-oscillators have been developed [23-27]. It could be demonstrated that with the thin disk laser design highest output powers are possible down to a pulse duration of 220 fs.

In the following chapters the results for q-switched lasers[28] and for pulse laser amplifiers are discussed in more detail.

4.1 Q-switched operation of the thin disk laser

Figure 8 shows the resonator design for the q-switched thin disk laser. The resonator is folded so that a short resonator length could be realized with a large mode area in the disk for fundamental mode operation. Q-switching is performed by a quartz acousto-optic modulator (AOM). Figure 9 shows the pulse energy as function of the repetition rate for Yb:YAG

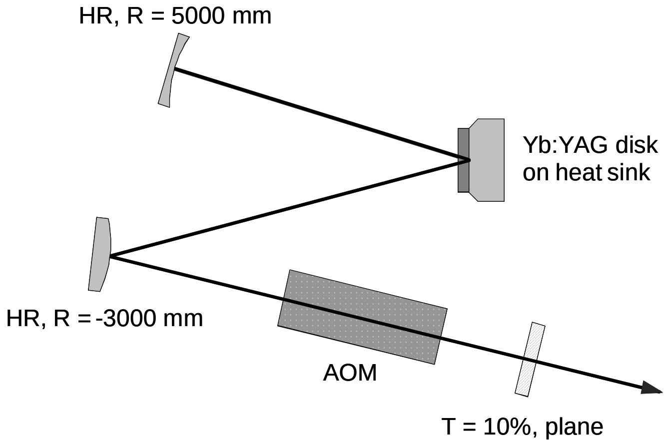

Fig. 8. Resonator design of the q-switched laser

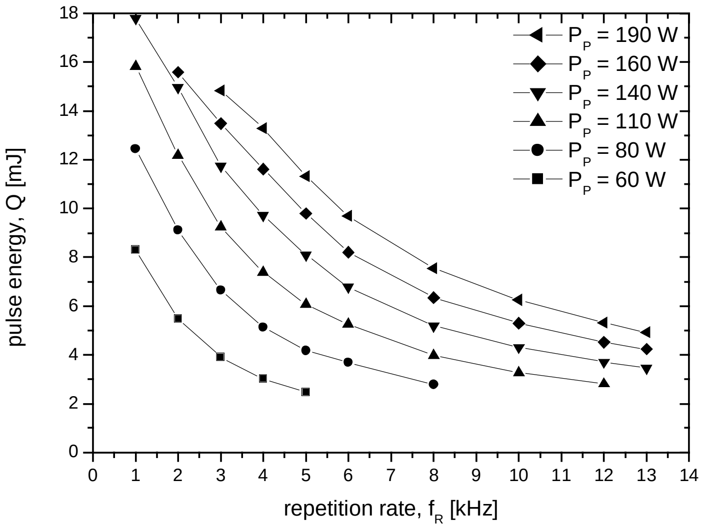

Fig. 9. Pulse energy of the q-switched thin disk laser as function of the repetition rate for different pump power levels

as laser active material. Stable operation could be achieved with repetition rates up to 13 kHz, while for higher repetition rates bifurcations of the pulse energy could be observed. The maximum pulse energy was 18 mJ at 1 kHz repetition rate and the maximum average power was 64 W at 13 kHz which corresponds to an optical efficiency of 34%. The beam propagation factor M^2 was better than 2 in all cases.

Figure 10 shows the pulse length of the pulses as function of the pulse repetition rate for different pump power levels. At low repetition rates the pulse duration is about 250 ns while for higher repetition rates the pulses become longer up to 570 ns at 13 kHz repetition rate. The reasons for these long pulses are on the one hand the length of the resonator

(840 mm for fundamental mode operation) and on the other hand the relatively low gain per roundtrip of the disk and hence the relatively high reflectance of the outcoupling mirror.

These restrictions in repetition rate (limited to frequencies below 13 kHz for Yb:YAG) and pulse duration (limited to pulse durations longer than 200 ns for the set-up used) could be overcome using thin disk amplifiers which are described in the next chapter.

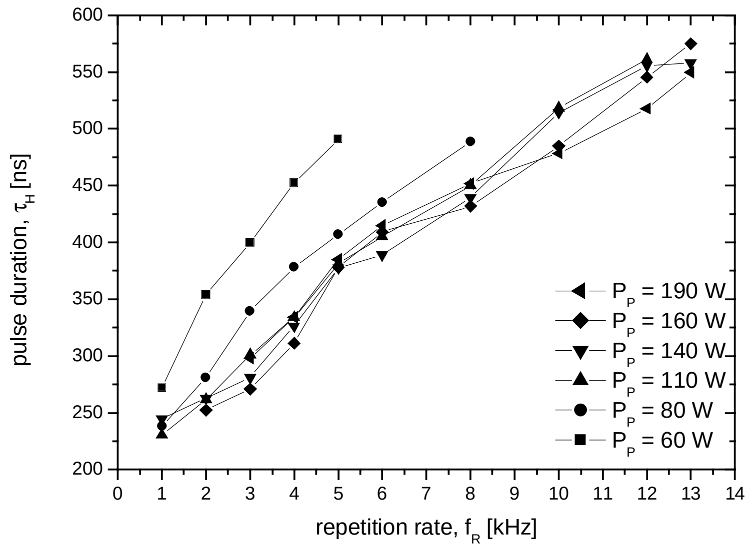

Fig. 10. Pulse duration of the q-switched pulses

4.2 Amplification of ns, ps and fs pulses

In order to produce shorter pulses with high pulse energy a set-up consisting of a master oscillator followed by a regenerative amplifier is used. The scheme of such a set-up in shown in Figure 11. The oscillator generates pulses with the desired properties (pulse length and wavelength) which are amplified to the desired energy in the thin disk amplifier. The thin disk amplifier in this scheme is operating independently from the seed laser and is able to amplify any incoming pulse with the right wavelength and a pulse duration shorter than the roundtrip time of the amplifier resonator.

For amplifying ps- or fs-pulses a seed oscillator with the appropriate pulse length (slightly shorter than the desired pulse duration after amplification) is used in combination with a Pockels cell and a TFP as pulse picker for reducing the repetition rate to the desired frequency.

A telescope is used for matching the mode of the oscillator to the amplifier and a separation unit containing a TFP and a Faraday rotator for the separation of the output pulse from the input pulse as shown in Figure 11.

The key components of the regenerative amplifier are the disk as amplifying medium, the thin film polarizer in combination with the Pockels cell as polarization switch for switching in and out the seed pulses and the amplified pulses, respectively. Additionally, for amplifying fs-pulses Gires-Tournois interferometer (GTI) mirrors can be implemented for compensating the positive group-velocity dispersion (GVD) of the Pockels cell and the optical elements during one roundtrip of the pulse inside the resonator.

Because of the small gain of the thin disk in the amplifier (10% to 40% per roundtrip, depending on the operational conditions) the pulses need between 50 and 200 amplifying roundtrips in the amplifier for achieving the desired pulse energy. Therefore it is very important to design the resonator in a way that the resonator internal losses are as small as possible. Otherwise the efficiency is reduced dramatically.

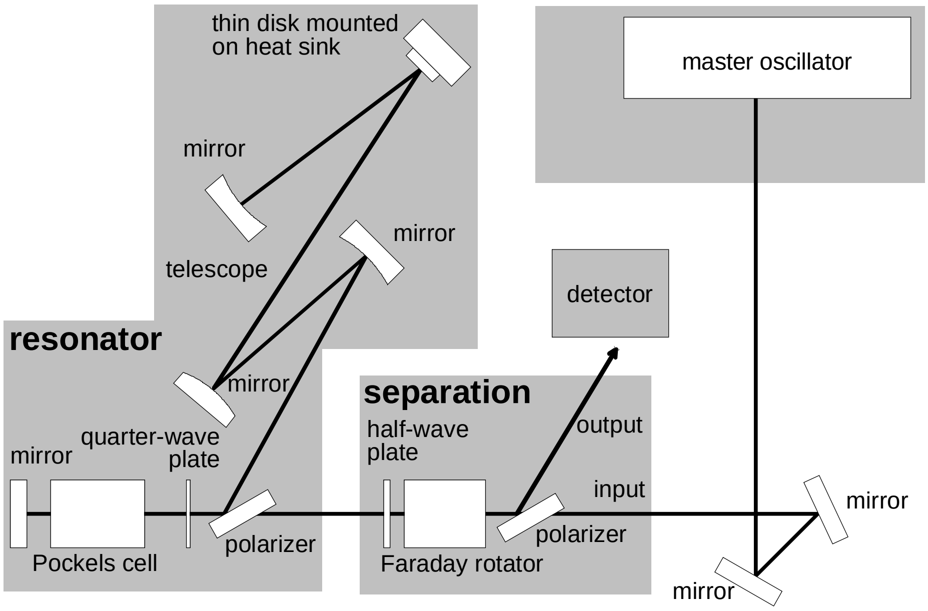

Fig. 11. Schematic set-up of an oscillator-amplifier system for pulse generation and amplification

Figure 12 shows an amplified pulse with a full-width-half-maximum (FWHM) pulse duration of about 8 ns with an energy of 33 mJ[29]. The maximum energy extracted so far is 37 mJ with a repetition rate of 1 kHz and a beam propagation factor $M^2 < 1.3$. Figure 13 shows the pulse build-up inside the amplifier resonator measured behind one of the resonator end mirrors. The mode diameter on the disk was 3 mm in these experiments. According to the scaling laws the energy can be increased further by increasing the pumped area and the mode diameter keeping the energy density constant.

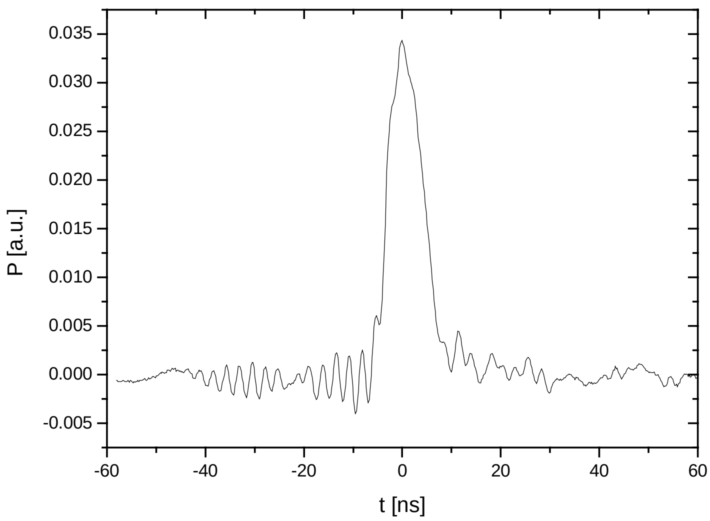

Fig. 12. Amplified ns-pulse from a regenerative amplifier (Yb:YAG)

Using a ps oscillator (pulse duration 1.8 ps) as seed laser in another set-up allows the amplification of ps pulses up to nearly 5 mJ energy at 1 kHz repetition rate and up to 1 mJ at 20 kHz[30-36]. Due to gain narrowing in the amplifier the pulse duration of the amplified pulses is extended to 4 ps. The beam is also for these pulses nearly diffraction limited.

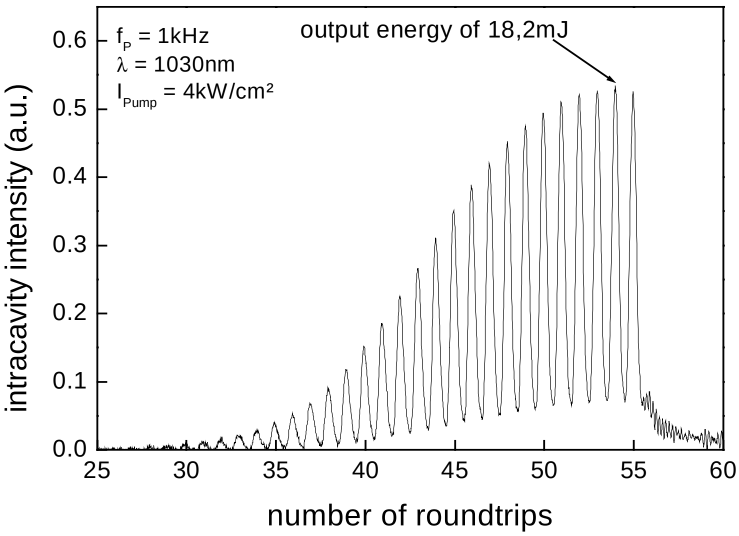

Fig. 13. Pulse build-up inside the regenerative amplifier

In another experiment we used Yb:KYW as laser active medium[37-39]. One advantage of this material is its much broader gain spectrum compared to Yb:YAG. Therefore even shorter pulses can be generated and amplified. In this experiment we used GTI mirrors for keeping the pulses short during the amplification. As seed laser we used an Yb:Glass oscillator delivering pulses with a pulse length of about 500 fs and an energy of about 1 nJ. These pulses have been amplified up to more than 100 µJ with a pulse duration of less than 900 fs. Figure 14 shows the pulse energies and the pulse widths for different repetition rates. At 45 kHz repetition rate a pulse energy of more than 100 µJ with a pulse duration of less than

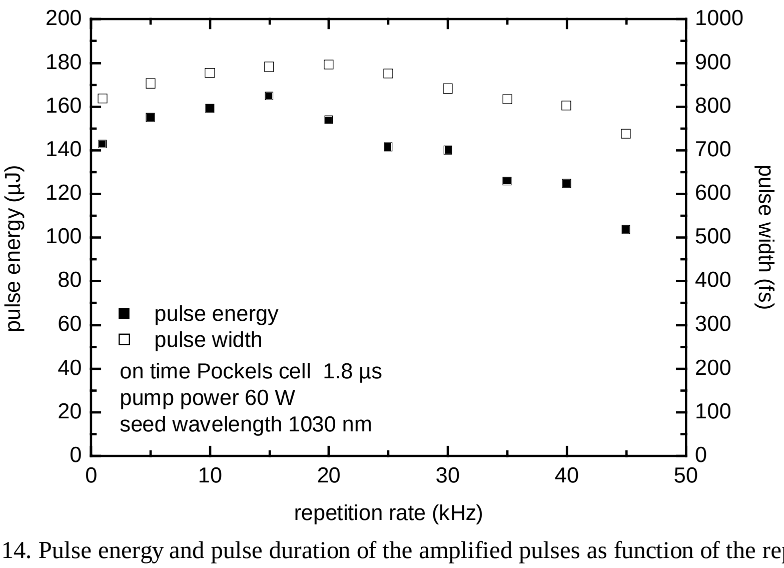

Fig. 14. Pulse energy and pulse duration of the amplified pulses as function of the repetition rate

800 fs could be demonstrated. In this case the average output power was as high as 4.5 W and it is remarkable that this result could be achieved without chirped pulse amplification (CPA). Due to the large beam diameter (2 mm in the Pockels cell) inside the amplifier the pulse lengthening by non-linear effects could be limited to pulse duration values below 1 ps. Figure 15 shows one of the autocorrelation curves.

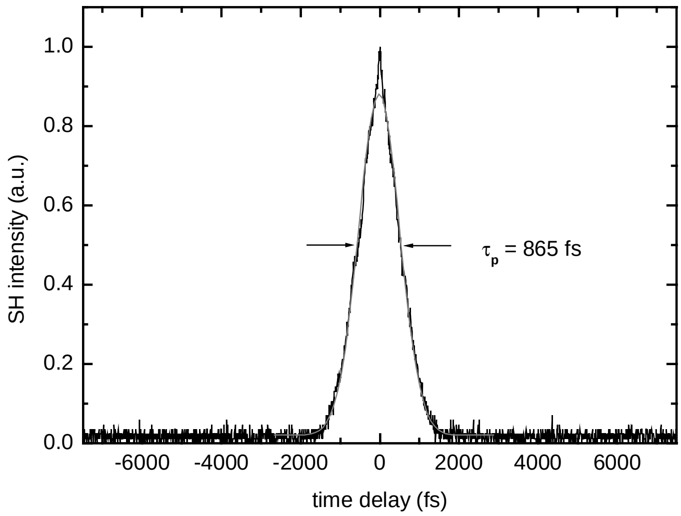

Fig. 15. Autocorrelation trace of the amplified pulses at a repetition rate of 15 kHz

From these results it can be seen that the thin disk laser design is able to generate and to amplify pulses up to high energy for all pulse durations between fs and ns pulse duration regime.

5. SEMICONDUCTOR THIN DISK LASER

Applying the thin disk laser design to semiconductor structures (e.g. quantum well structures) it is possible to adapt the laser wavelength to the demands of the application because quantum well structures can be designed to the desired wavelength (in the range between 630 nm and 2000 nm and even outside this range) whereas solid state laser materials are limited to the spectral range or line which is given by the laser active material. Additionally, the wavelength regime between 315 and 630 nm can be achieved with quantum well structures by frequency doubling of the fundamental wavelength above 630 nm. Consequently, the complete wavelength range above 315 nm up to the mid-infrared can be addressed which is very advantageous for all the wavelength specific applications.

In the past, some groups used this design for building semiconductor thin disk lasers in the 1 µm wavelength regime in the power range of 8 W[40] and 27 W[41], respectively. By frequency doubling also the wavelength range around 500 nm could be demonstrated. These lasers have been pumped at a wavelength which is more than 15% shorter than the laser wavelength using the absorption in the spacer layers between the quantum wells. The disadvantage of this pump principle is the large quantum defect between pump- and laser-photon which yields in a rather high temperature inside the lasing structure.

To overcome this disadvantage we apply the concept of the thin disk laser in such a way to semiconductor structures that we pump directly into the quantum wells using a wavelength which is less then 5% shorter than the laser wavelength. In this way we are able to reduce the waste heat and the temperature in the structures so that we can operate the structures in principle with higher efficiency and also at higher temperature. Also the scalability to higher power is easier since the increase of the pump spot is not so sensitive to the waste heat flux conditions. In addition, materials with higher temperature sensitivity (e.g. between 600 nm and 700 nm wavelength range) can be operated much easier[42]. The

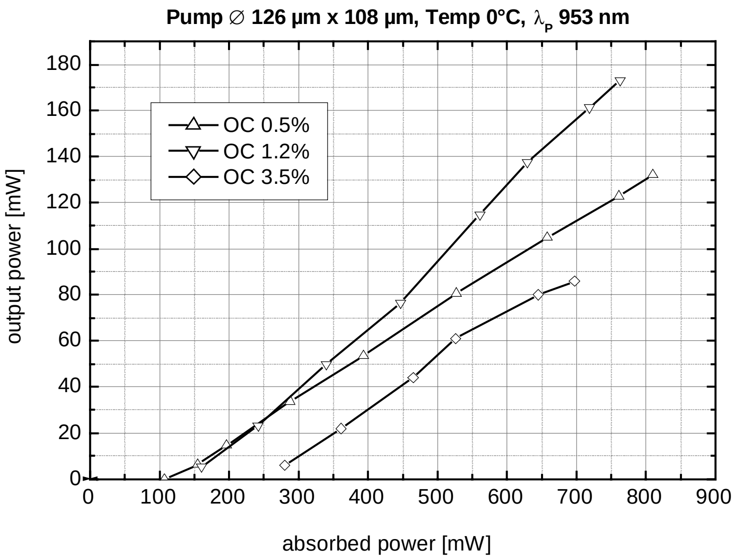

Fig. 16. Lasing properties of quantum well pumped semiconductor structure, lasing wavelength 1036 nm

disadvantage of a very low absorption when pumping directly into the quantum wells can be overcome by our multi-pass pump design also used for the solid-state thin disk laser.

First results using direct quantum well pumping are given in Figure 16. This picture shows the lasing behaviour of an infrared semiconductor structure at 1036 nm lasing wavelength, pumped at 953 nm. At 770 mW absorbed pump-power more than 170 mW laser power have been achieved. Figure 17 shows also quantum well pumping but for a lasing wavelength between 652 nm and 656 nm, pumped at 628 nm. At 400 mW pump power more than 140 mW laser power could be demonstrated. These very first results demonstrate clearly the potential of semiconductor thin disk lasers especially if they are pumped directly into the quantum wells.

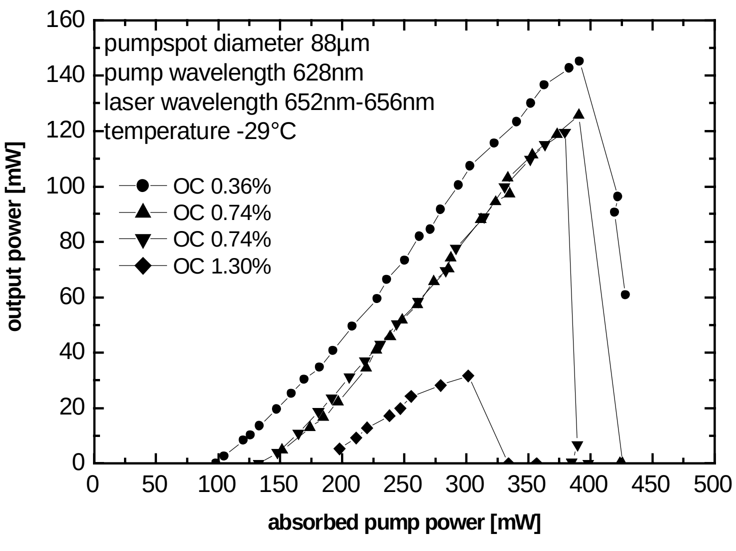

Fig. 17. Quantum well pumping of red semiconductor structure (Epi-structure from Osram OS)

6. INDUSTRIAL REALIZATIONS

Up to now 15 licences of the thin disk laser design have been sold to companies worldwide. Some of these companies already offer thin disk lasers on the market.

Rofin-Sinar Laser GmbH offers lasers for materials processing with output powers of 750 W and 1.5 kW coupled into an optical fibre with 150 µm core diameter (N.A. = 0.2). Trumpf Laser GmbH + Co KG offers thin disk lasers with 1 kW and with 4 kW output power also coupled into fibres with 150 µm or 200 µm core diameter. Because of the good beam quality of these lasers which is comparable to that of CO_2-lasers in the same power range these lasers are excellent for high power materials processing.

Jenoptik Laser, Optik, Systeme GmbH is selling high power lasers in the green, red and blue spectral range (up to 8 W green, 0.8 W blue, 2 W red) and also q-switched thin disk lasers for marking and drilling. Elektronik Laser System (ELS) offers fundamental mode thin disk lasers with up to 100 W cw in the fundamental wavelength and up to 15 W frequency-doubled into the green spectral range.

These examples show that the thin disk laser has found its way from the laboratory to real applications in industry successfully. More companies will enter the market within the next few years.

7. SUMMARY

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

In future, new materials will be investigated with the goal to increase the power, the energy and the beam quality furthermore. Laser output powers of more than 10 kW and energies of more than 1 J will be possible. New materials will open new markets for new wavelengths and with the semiconductor thin disk laser customized lasers for specific markets will become feasible.

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