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The History of Thin-Disk Laser Development

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This paper describes thin-disk laser history starting with the industrial laser environment in Germany in the 1970s. The background of the invention is discussed along with the German political and research environment. Thin-disk laser design and performance are then discussed in detail. Results for continuous-wave and pulsed operation as well as for amplification of short (nanosecond) and ultra-short (picosecond, femtosecond) pulses demonstrate the potential of thin-disk laser design. Advantages for using various laser materials are explained, as well as applicability of the thin-disk laser concept to optically pumped semiconductor structures. Finally, an overview is presented of German research and development practices and of patenting and licensing policies. The last section describes industrial applications of thin-disk laser technology.

KEYWORDS: Solid-state laser, Thin disk laser

1. Introduction

Thin-disk laser design for diode-pumped, solid-state lasers allows for high output power, high efficiency, and good beam quality. The laser disk principle was first demonstrated in 1993, and during the first laser run in 2006, 6.5-kW output power was achieved with a single disk. At present, using four disks in a single resonator allows for output power extraction of more than 20 kW. Thin disk lasers of up to 16 kW are commercially available for materials processing. The beam quality (focusability) of all commercially available thin disk lasers is always better than that for rod lasers with similar power. In addition, electrical efficiency is higher than all other commercially available solid-state lasers with similar power.

Thin-disk laser design also allows highly efficient pulsed operations such as q-switched laser, cavity-dumped laser, or laser amplification (regenerative or multiplass). Generation and amplification of ultra-short pulses are possible with very high average power and high efficiency. These properties of thin disk lasers ultimately launched a completely new class of ultra-short pulsed laser systems for materials processing and other applications.

Due to the increased focusability of thin disk lasers compared to rod lasers, either a significant reduction of the focus diameter by using the same focusing optics or an increased working distance with the same diameter of the focus can be achieved. The latter enables highly productive techniques like remote welding, which uses rapid beam deflection, to eliminate laser nonproductive idle time during movement of the beam or the work piece from one weld spot to the next one. In the past, because of insufficient focusability of lamp or diode-pumped rod lasers, remote welding was possible only with CO_2 lasers.

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Thin disk lasers will not only replace classical laser systems in many applications, but will also open up new markets for laser technology that require certain specific properties of thin disk lasers that cannot be met by classical laser systems.

1. Background and Proof of Principle

1.1. The industrial laser environment in Germany up to late 1980s

In the 1970s, the first high power CO_2 lasers, made by U.S. companies, became available for materials processing. These lasers were used for cutting and welding of metal sheets. The power of the first lasers was 500 W, which later increased to 1 kW. Immediately, CO_2 laser development for industrial lasers started all around the world. The goal was to achieve higher laser output power and better beam quality, such as focusability, and especially greater reliability. In 1982, the German company Trumpf, together with the Institute of Technical Physics (DLR-TP) of the German Aerospace Center (DLR, formerly DFVLR, German Aerospace Research Establishment), commenced a laser research program using the radio-frequency (RF) excitation technique developed at DLR-TP since the late 1970s. Trumpf succeeded with this technique and entered the market in 1986. Meanwhile, the Rofin-Sinar company started developing high power CO_2 lasers and succeeded first with fast axial flow–type lasers, and later with diffusion-cooled slab lasers; the technology of the latter was transferred from DLR-TP to Siemens and then to Rofin-Sinar. Both Trumpf and Rofin-Sinar became market leaders in the field of high power CO_2 lasers for materials processing.

In the early 1970s, at about the same time as industrial CO_2 laser development began, so too did research and development of the Nd:YAG laser for industrial applications. The first of these was a flash-lamp pumped, pulsed laser system, used especially for spot welding. In Germany, the Haas-Laser company built such lasers first for spot welding of flat spiral springs and later for spot welding of cathodes in TV tubes (for AEG Telefunken and Philips). Later, lasers with high average power (several hundred watts) and higher repetition rates were developed for metal sheet welding.

In the 1980s, discussion arose about the best laser wavelength for materials processing. People in favor of the CO_2 laser argued that it was already quite well developed, it could be operated up to several kilowatts of cw power, the beam quality (focusability) was very good ($M^2 \approx 2$), and wall-plug efficiency was about 10%. Arguments in favor of the Nd:YAG laser asserted that the much shorter wavelength (by a factor of 10) allows for (theoretically) better focusability (also by a factor of 10), higher absorption by metals also due to the shorter wavelength, and the possibility of beam delivery using quartz fibers (e.g., Dausinger[16] and Dausinger et al.[17]). The latter argument was very important since for CO_2 lasers, only free-space beam delivery was possible to bring the power from the laser to the work piece. This means that the laser had to be installed and adjusted in a fixed position vis-à-vis the materials processing machine, with an accuracy <100 μm and often <10 μm.

Consequently, development of high power Nd:YAG lasers for materials processing began. First, in the late 1980s the Japanese company NEC brought a lamp-pumped Nd:YAG laser to market with 1 kW of cw power that was used mainly for welding applications. Haas-Laser followed a few years later with its own Nd:YAG laser in the kilowatt class. These lamp-pumped lasers were and still are widely used for welding applications, although efficiency is quite low (<3%), and focusability is poor compared to CO_2 lasers (by a factor of 5). The advantages of the shorter wavelength could not be exploited in real-world systems; therefore, Nd:YAG lasers were not used in applications for which precision focusability is essential, such as high-speed cutting applications. The advantages of fiber delivery of laser power opened the market for these lasers since it became possible to keep the laser source in a remote position and to bring laser power to the work piece using flexible fibers, which results in simplified system architectures. It was also possible to very quickly switch the laser power from one work piece to another by switching the laser power from one fiber to another.

Meanwhile, new concepts for high power laser diodes were developed and tested, making it possible to operate laser diodes with about 1 W of output power at room temperature. With the introduction of the first laser bars, several watts became available. Operated at 808 nm, diode lasers have been used for pumping Nd:YAG crystals, achieving high power (tens of watts) and thus demonstrating the potential of diode-pumped solid-state lasers. At that time researchers could already demonstrate the higher wall-plug efficiency of diode-pumped, solid-state lasers due to the high wall-plug efficiency of laser diodes (30% to 40% at the time). With this technique, the wall-plug efficiency of Nd:YAG lasers could later be increased to values higher than for CO_2 lasers. But, while the expectations regarding wall-plug efficiency were met, dramatic improvement of beam quality (focusability) due to lower waste heat generated when pumping with laser diodes could be demonstrated only at low power. It has been found that restrictions of rod laser systems regarding beam quality are very hard to overcome for high power laser systems. Even 20 years after this development began, the focusability of industrial multikilowatt, diode-pumped, rod laser systems is 60 to 80 times less than the theoretical limit.

These limitations of rod laser designs led to new concepts for high power solid-state lasers. In the early 1970s, disk lasers and disk amplifiers had already been developed especially for high-pulse energies. This disk design is able to generate high energy, but if beam quality is important the repetition rate is limited due to low cooling efficiency. Another design that has been discussed since the mid-1980s is the slab laser, which is still used because the optical distortions inside the laser active medium can be partially compensated. Many groups began the search for alternative laser active materials that could be used for diode laser pumping, especially at Lawrence Livermore National Laboratory (LLNL), Stanford University, and Massachusetts Institute of Technology (MIT), who tested many different rare earth ions in diverse host crystals.[18,41]

1.2. Laser institutes in Stuttgart, Germany

The Institute of Technical Physics (DLR-TP) of the German Aerospace Center (DLR, formerly DFVLR, German Aerospace Research Establishment) has investigated concepts for high power gas lasers since 1974. In this framework, the first RF-excited CO and CO_2 lasers were developed. Already in 1982, a CO_2 laser with 5-kW output power could be demonstrated using stable and unstable resonators. The RF-excitation technique using dielectric electrodes results in an extremely homogeneous and stable discharge over a large cross-section ($4 \times 4 \times 48$ cm^3 for 5-kW laser output power) for extremely good beam quality. In addition, power density was very high. Since 1982 this technology was transferred from DLR-TP to Trumpf with the financial support of the German Ministry of Research and Technology (BMFT; today the Ministry of Education and Research, BMBF). Subsequently, Trumpf developed its own RF-excited, fast-axial-flow CO_2 lasers and entered the market in 1986. This CO_2 laser was the beginning of Trumpf's success as a leading German company in industrial laser applications.

The RF-excitation technique for CO_2 lasers was also transferred to Rofin-Sinar, first in its fast-axial-flow CO_2 lasers, and later in CO_2 slab lasers that were developed by Siemens and DLR-TP, and later in cooperation between Rofin-Sinar and DLR-TP.

Uwe Brauch and his team at DLR-TP started working on solar-pumped rod lasers in the late 1980s, and the group started pumping these rod lasers using diode lasers of about 1 W laser power each in 1990–1991.

In 1986, the University of Stuttgart's Institut für Strahlwerkzeuge (IFSW) was established. Helmut Hügel and I left the CO_2 laser group at DLR-TP; Hügel became director of the new institute, and I was responsible for laser development and laser optics at the IFSW. During the Institute's early years, CO_2 laser properties were improved in close cooperation with Trumpf. Meanwhile, Friedrich Dausinger developed the basics of materials processing (cutting, welding, and surface treatment) with high power lasers. These investigations indicated that the shorter wavelength of Nd:YAG lasers would be advantageous for materials processing. At that time, many groups around the world were working on diode-pumped rod lasers. In strategic meetings at the IFSW in this period, I refused to commit the Institute to developing these lasers, at least until promising new concepts had been developed. Consequently, beginning in 1990 I attended a number of conferences in the search for new ideas about solid-state laser technology.

1.3. The initial concept

In November 1991, I visited the LEOS '91 conference in San Jose, CA, where I attended many talks about solid-state lasers. On November 6, I was fascinated by a talk given by T.Y. Fan of MIT's Lincoln Laboratory. Fan discussed results achieved using Yb:YAG as the laser active medium. He explained in detail the advantages of Yb:YAG compared to Nd:YAG, and stated that Yb:YAG was by far the better laser active material for diode laser pumping. But he also explained the difficulties of Yb:YAG as the laser-active material that results from the quasi-three-level nature of the Yb ions. The very small quantum defect (only 9%) of Yb:YAG pumped at the 940-nm wavelength and emitting at the 1030-nm wavelength leads to a population of the lower laser level at room temperature of about 4%. Therefore, rather high pump power density has to be applied to reach threshold. Simultaneously, the temperature of Yb:YAG has to be kept low. Otherwise, the pump power density has to be increased even more since the population density of the lower laser state and with this the laser threshold increases with increasing temperature. For these reasons, the classical rod laser design was inadequate for this quasi-three-level laser material. Fan and coworkers demonstrated 1.56 W output power from a very small crystal volume, laser beam pumped. Fan finished his talk with the remark that in principle, very high laser output power with high optical efficiency could be obtained from Yb:YAG if a way to effectively remove the waste heat were found. He stated that for a crystal with the dimensions $2 \times 2 \times 0.4\ mm^3$, pumped with 190 W, 100-W laser output power should be possible. This statement started me thinking about possibilities of building such a laser.

During the trip from California to Japan and then back to Germany, my first calculations showed that it should be possible to achieve high output power with very thin crystal sheets cooled from one face or from both faces so that the waste heat has to pass only a very short distance to the cooled surface. In this way, I thought, the output power should be scalable just by increasing the area of the crystal while keeping the thickness constant.

1.4. The work begins

Back at the institute, I told my colleagues (Helmut Hügel, Friedrich Dausinger, Peter Berger) about the idea to use Yb:YAG as the laser-active medium with a new design for starting the work on diode-pumped solid-state lasers. During several discussions before year-end 1991 with Hügel, Dausinger, and Berger (all at IFSW), and later Hans Opower (director of DLR-TP), I explained my ideas and a plan to form a group to develop details and to test a complete new design for diode-pumped solid-state lasers. Opower supported these ideas very strongly and he suggested including Uwe Brauch in such a group. At the end of 1991, Hügel agreed to this plan and so, early in 1992 the group began working on the new concept. Group members were Andreas Voss, Klaus Wittig, and me from IFSW, and Uwe Brauch from DLR-TP. The group met every Friday afternoon for an open-ended discussion about the new Yb:YAG laser system. And at the end of the meeting, everybody received homework for the next Friday. Within 3 months, details of the thin-disk laser design had been developed and proven by simulations.

In late March 1992, I contacted the VDI-TZ (Technology Center, German Association of Engineers), the project execution organization for the German Ministry of Research and Technology (BMFT), about the new ideas and prospects for a project funded by the BMFT. Fortunately, a collaborative effort between German institutes and industry was already underway on diode-pumped solid-state lasers using Nd:YAG with rod and slab designs. For this collaborative project, an extension phase (December 1992 to December 1993) was planned and VDI-TZ intended to include IFSW and DLR-TP in this phase. Design details were discussed with VDI-TZ people, but they were asked to avoid disclosing the same to project partners until the University of Stuttgart and DLR had applied for respective patents. This was critical because the institutes needed financial support from industry of 25% of total project costs. Discussion was characterized by controversy during two meetings attended by all project partners regarding new ideas (Yb:YAG as laser active medium and a completely new design that we did not disclose) and possible support from industry. Most of the companies did not want to support even the promise of a new design since they did not believe that Yb:YAG would serve for a high power laser because of its quasi-three-level nature.

But Siemens (today Osram) and Zeiss believed that using the new material and a new laser design would be advantageous. Werner Späth from Osram stated that the lifetime of laser diodes for pumping solid-state lasers could be increased dramatically if a bit of indium were used in the laser diodes (InGaAs instead of AlGaAs, which is used for pumping Nd:YAG). However, the laser wavelength is shifted to a longer wavelength region (beyond 900 nm) so that Nd:YAG cannot be pumped with longer lifetime diodes. But if Yb:YAG can be operated as high power laser material, InGaAs diodes operating at 941 nm can be used. Although today the lifetime of high power laser diodes is high enough for industrial applications (more than 20,000 hours), the argument for longer life of InGaAs laser diodes was a very important one in the 1990s. Harald Sakowski from Zeiss supported the new idea

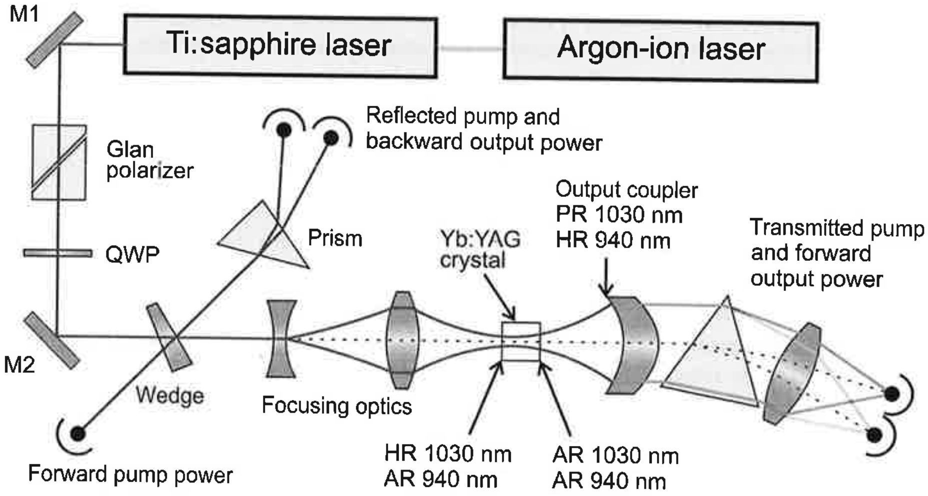

Fig. 1. Experimental setup of the Ti:sapphire laser–pumped Yb:YAG laser.

since Zeiss was developing highly compact solid-state lasers for many applications, and he believed that with Yb:YAG even more compact solid-state lasers could be built.

As a result, at the end of the second meeting financial support from Siemens and Zeiss was approved for a first project that ran from December 1, 1992, to December 31, 1993. In this effort, Siemens delivered the laser diodes for pumping and Zeiss polished and coated the Yb:YAG disks, a small rod, and a small slab for the research.

2. The First Experiments

2.1. Measurements of Yb:YAG properties

In summer 1992, the first experiments began. Delivery of the disks and laser diodes for pumping was scheduled for spring 1993. But first, Zeiss polished and coated a very small rod (diameter 2 mm, length 2 mm) for experiments using an Ar-ion–laser-pumped Ti:sapphire laser that students normally used in experimental courses. One side of the tiny rod was AR-coated for the laser and the pump wavelength (R < 0.12% for 1030 nm and 940 nm), while the other side was AR-coated (T > 97%) for the pump wavelength and high reflection (HR) coated (R > 99.8%) for the laser wavelength. In these first Ti:sapphire-pumped rod laser experiments, we determined laser parameters, such as power, threshold, and efficiency for crystal temperatures between 100 K and 340 K, similar to the experiments performed by T.Y. Fan. Fig. 1 shows the experimental setup, and Fig. 2 shows the laser output power versus absorbed pump power for an output coupler reflectivity of 90%. In this setup we used longitudinal pumping. For optimizing the absorbed pump power and the pump power density, the output coupler was HR coated for the pump wavelength.

Figure 3 shows the slope efficiency and the extrapolated threshold for the absorbed pump power versus crystal temperature for the pump wavelengths 940 nm and 969 nm. The first laser action was demonstrated on December 22, 1992. In the experiments, pumping

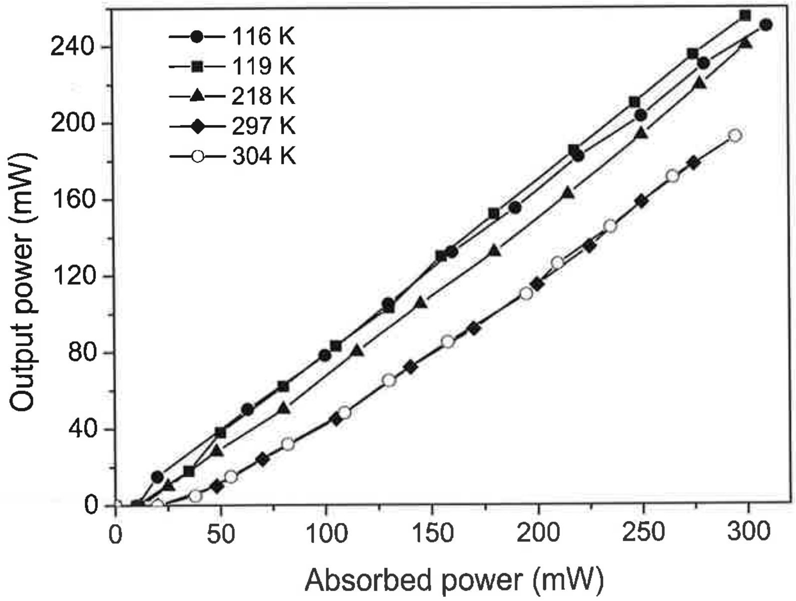

Fig. 2. Output power of the Ti:sapphire–laser pumped Yb:YAG laser at 1030 nm versus the absorbed pump power at 969 nm.

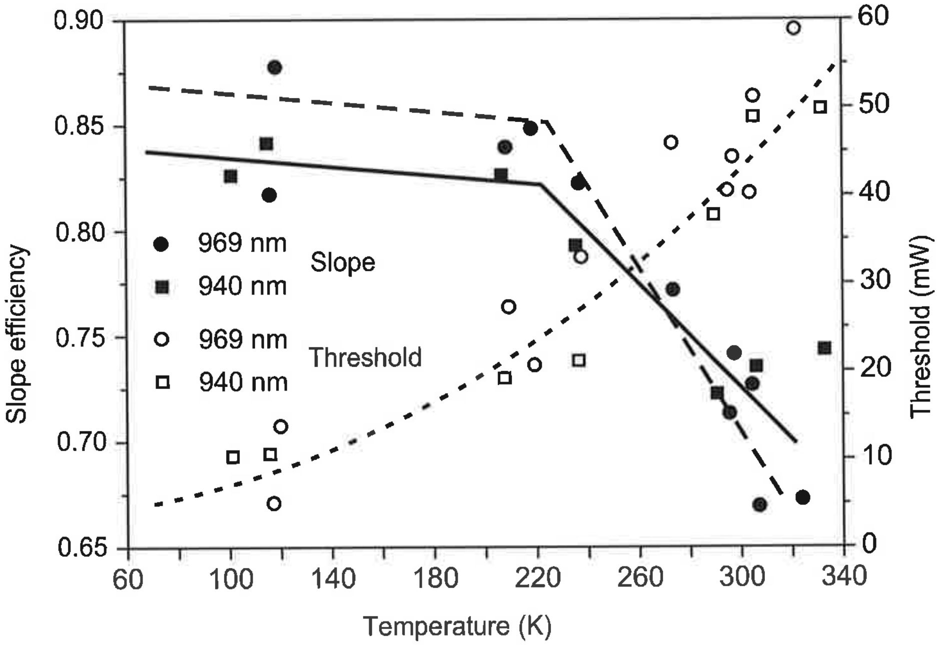

Fig. 3. Slope efficiency and extrapolated threshold for the absorbed pump power of the Ti:sapphire–laser pumped Yb:YAG laser versus temperature for pump wavelengths 940 nm and 969 nm, respectively.

directly into the upper laser level (pump wavelength 969 nm) was also shown. The high potential of Yb:YAG was clearly demonstrated, resulting in more than 80% slope efficiency (laser power vs. absorbed pump power).

The tiny rod for the first experiments was made from a 20% doped Yb:YAG piece that the Litton company had given to Zeiss for development. When thinking about using this material for the first disks, the optimum thickness was calculated to be much less than 200 μm. This seemed to be too thin and too difficult to produce. Therefore, Yb:YAG material with a lower doping concentration was chosen for the first experiments. During a conference, I met Ralph Hutchinson from Scientific Materials and discussed whether his company could grow Yb:YAG boules. Hutchinson was very helpful and he offered four boules (5%, 10%, 15%, and 20% doping concentration) for a very reasonable price. After receiving the four boules, the 10% doped material (later we found that the real doping concentration was 9%) was used for the first disk laser (disk diameter 2 mm, disk thickness 300 μm).

Note: Years later when optimizing the thin-disk laser design, Yb-doped materials with doping levels of 15% and 19% were tested for reducing disk thickness and for reducing the temperature increase inside the disk. Laser operation has never been achieved, since all the highly doped disks burned away before reaching laser threshold. The reason for this behavior is doping and impurity–dependent nonlinear decay of the excited state in Yb:YAG, which results in a strong temperature increase in the disk. Evidence of this phenomenon was published in 2005. The decision to use the 10% doped Yb:YAG for the first disks was very fortunate, since we did not know all the properties of the highly Yb-doped materials at the time.

2.2. The first thin-disk laser experiments

In spring 1993, the laser diodes from Siemens and the first disks from Zeiss were delivered and development of the first thin disk laser could begin. Twenty-four laser diodes from Siemens with 0.7 W each at the end of a delivery fiber (core/cladding diameter 125/140 μm, N.A. 0.37) were used for pumping the disk. All the cleaved fiber ends were bundled together to a diameter of 0.8 mm. resulting in a total power of 16.8 W. With an aspherical lens system, the fiber bundle was imaged onto the disk surface resulting in a pump spot diameter of 0.95 mm and a total pump power of 12 W on the crystal surface. For increasing the effective pump power density and the absorbed pump power, the unabsorbed part of the pump power was re-imaged to the disk again using a lens and a flat mirror (Fig. 4). With this setup, more than 2 W output power for 6.5 W absorbed pump power was achieved (Fig. 5). For this experiment as well, the problem of fixing the disk onto the cooling device was solved. An indium foil (50 to 100 μm thick) was used for a cold fusion process. The indium foil was placed between the water-cooled copper cooling plate and the disk, and then this sandwich was pressed together so that the thickness of the indium was nearly half after the pressing procedure compared to the original foil thickness. The waste indium flowing out at the edge of the disk was cut using a knife.

These experiments demonstrated that materials like Yb:YAG could be used as the laser active medium in the thin-disk laser design. It was also absolutely clear that a scalable concept for building high power diode-pumped, solid-state lasers was discovered. Using the thermal lensing design was less by two orders of magnitude compared to classical rod

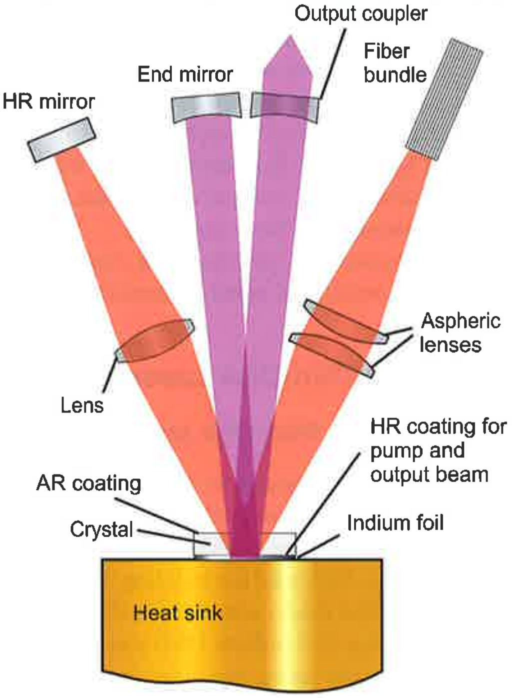

Fig. 4. Schematic setup of the diode-pumped Yb:YAG laser.

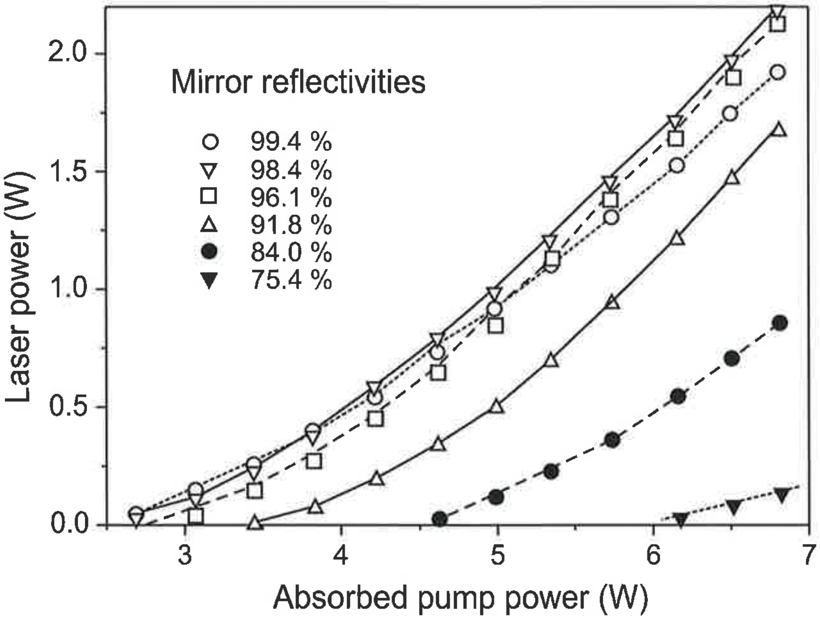

Fig. 5. Output power versus absorbed pump power of the diode-pumped Yb:YAG laser for various output coupler reflectivities at 285-K cooling fluid temperature.

lasers. And in December 1993, the first paper was sent to *Applied Physics B*[26] with all the design ideas and the calculated and measured data. Also a post-deadline paper at the 1994 Advanced Solid-State Lasers (ASSL) was accepted for presentation. In this paper, it was stated that the thin-disk laser design is a power-scalable design for diode-pumped solid-state lasers, and in the summary an optical-to-optical efficiency of about 50% at room temperature and 70% at 200 K (cooling fluid temperature) was predicted. In addition, a laser output power density of about 5 kW/cm² per crystal disk was predicted. Today, all of these values have been demonstrated and even surpassed.

All these experiments and studies were performed in close cooperation between IFSW and DLR-TP. Experiments were performed in the laboratories of both institutes.

3. Developing Thin-Disk Laser Architecture

3.1. Scaling thin-disk laser power

In late summer 1993, the 2-W thin disk laser was presented to the project partners. Some were quite excited by the results and the predictions; others had doubt about scalability. Nevertheless, VDI-TZ asked for a project proposal for scaling experiments funded by BMFT. The proposal submitted to VDI was for building a 1-kW thin disk laser with up to four disks for a total 7 million DM (today about 3.5 million euros), to take place over a 3-year period. Only half the funding (3.5 million DM) was obtained, and thus, the parties agreed to build a 500-W thin disk laser using two disks in a single resonator.

For this project, 200 additional fiber-coupled laser diodes were purchased from Siemens, each 1.2 W at the fiber end. At the same time many fiber-coupled laser diode bars were ordered from another German company. Unfortunately, the latter company could not meet the specifications, so all bars were returned to the company. Another German company also failed to deliver the diode bars within the specifications. Then, at the Laser Fair 1995 in Munich, I visited the booth of the Tucson-based Optopower and met with Meryll Apter. Optopower offered high power laser diode bars at the 808-nm wavelength for pumping Nd:YAG. I asked Apter whether Optopower was also able to deliver fiber-coupled laser diode bars with a 940-nm wavelength for our Yb:YAG thin-disk laser scaling experiments. Apter then asked how many diode bars would be needed, and when he heard that for the first experiments 38 units with 20 W each at the end of the fiber bundle were necessary, he promised to work on these laser diodes. Optopower sent a quotation and the high power laser diode bars for pumping our disks were ordered. At the end of 1995, the first high power laser diode bars with 20 W at the end of the fiber bundle and at 940-nm pump wavelength arrived in Stuttgart.

With the diode lasers from Siemens and later with the diode laser bars from Optopower, the scaling experiments could start. Already in 1995, details of the 40-W thin disk laser at 136-W pump power, using the laser diodes from Siemens, were published. Also single-frequency output power of 14 W was demonstrated. In 1996, the power level was increased to 147 W from one disk using the first laser bars from Optopower (pump power of 340 W). With an increased number of laser diode bars from Optopower, 255 W were demonstrated in 1997 with 49% optical efficiency,[13] and in 1998 thin-disk laser power reached 346 W (700 W pump power).[34] In addition, the fundamental mode power was increased to 100 W and the single-frequency power to 28 W.

To achieve these results and scaling the power of one disk from 2 W to 346 W within 5 years, it was necessary to develop the technology of combining pump power from many laser diodes. When using the diodes from Siemens, all the individual fiber ends were bundled together to a single fiber bundle with the smallest possible diameter. The end of this fiber bundle was imaged onto the disk (passes 1 and 2, first double pass) using a first spherical mirror. The unabsorbed pump power was then re-imaged (second spherical mirror) to a plane mirror close to the disk and it was reflected to the orthogonal plane. Then the pump radiation was imaged (using the third spherical mirror), again onto the disk (passes 3 and 4, second double pass). With the fourth spherical mirror, the unabsorbed pump radiation was imaged back all the way toward the fiber bundle, resulting in passes 5 to 8 through the disk. Consequently, a total of 8 passes of the pump radiation through the disk were realized using this design. One disadvantage of the design was the first image of the fiber bundle onto the disk. For achieving high efficiency, pumping the disk with a nearly flat top pump profile is desirable. In this case, the imaging reproduces the intensity distribution at the end of the fiber bundle onto the disk so that all the individual fibers can be seen. This results in a modulated intensity and temperature profile. This modulated profile can be partially reduced by slightly detuning the succeeding pump beam passes.

Imaging each emitter separately to the disk, and thus illuminating the complete pump spot is more efficient. This technique was realized with the fiber-coupled laser diode bars from Optopower. In this case, every single-laser diode bar coupled into a fiber bundle (19 individual fibers for the 19 emitters) was imaged onto the disk so that each bar illuminated the complete pump spot. For this imaging, a lens array in a hexagonal arrangement had to be used so that the aperture of the spherical mirrors for the re-imaging process was completely filled. The highest pump power density can be achieved using 1 bar, 7 bars, 19 bars, or 37 bars, with the appropriate number of lenses and the right focal lengths. Especially for high numbers of bars, the pump profile is much more homogeneous than with the fiber bundle since all pump profiles are overlapping and each bar is illuminating the complete pump spot.

During the early years, Lothar Ackermann from FEE (Forschungsinstitut für mineralische und metallische Werkstoffe-Edelsteine/Edelmetalle GmbH) in Germany agreed to grow Yb:YAG boules for thin disk lasers. But when he saw our thin-disk laser design, he said that only a relatively small number of boules would serve for making all the disks necessary in real-world industrial production. FEE could also polish crystals; therefore, Ackermann initiated thin disk polishing. This was the beginning of a longtime cooperative effort. Today, FEE is able to grow boules with a flat interface (without core and striae) up to a boule diameter of more than 70 mm, which can be used as disk material using the full cross-section of the boule.

3.2. Thin disk coating and mounting

Another very important topic is disk coating and mounting. As mentioned previously, the first disks were fixed on the cooling plates using indium between the disk and cooling plate. But, upon scaling the output power of the disk, several problems resulting from this fixing method were realized. The first was the low tensile strength of indium. When increasing the pump spot diameter and/or reducing the thickness of the disk, indium's tensile force may become higher than its tensile strength. This results in a residual plastic deformation of the sandwich after operation. This problem was solved by soldering the disk onto the heat sink, first by using indium alloys, and today by using gold-tin as solder, which shows the highest tensile strength of all usable solders. However, due to the high melting temperature of gold-tin (≈300 °C) it is necessary to use a heat expansion–matched cooling plate, such as CuW.

Soldering the disk onto the cooling plate can also solve a second problem resulting from the cold fusion process. Due to very high stress in the sandwich (crystal-indium-cooling plate), the shape of the sandwich after the pressing procedure is not ideally planar or spherical. After relaxing the pressure to the sandwich, typically some nonspherical distortions can be found. These are between ~10 nm and ~100 nm within the pump spot, and result in additional losses especially for lasers with good beam quality. Therefore, when soldering the disks, the disks were permitted to swim on top of the molten solder without pressure, so that the disks were able to come to their original shape. After cooling down, the disks showed a nearly perfect spherical shape with residual errors in the nanometer range only.[42] Another method to fix the disks on the cooling plates was gluing the disks on the cooling plates using epoxy. In this case, the thickness of the epoxy has to be less than 1 μm because of the low heat conductivity of epoxy. In addition, gluing the disks on the cooling plates with low optical distortion similar to those in the soldering process described is difficult.

The third problem occurs especially at high output power using large pump spots. In this case, the absorption of spontaneous emission and amplified spontaneous emission (ASE) in the solder results in raising disk temperature, thus reducing efficiency. Therefore, to reduce absorption in the solder, special coating designs were used. These designs consist of a dielectric coating for reflecting the pump and laser wavelength on the back side of the disk, followed by a copper mirror for reflecting the fluorescent and ASE power, followed by a soldering stop and metal layers for the soldering process.

For very high output power, the disk may be mounted behind an undoped thicker disk of YAG.[39] The fixing can be performed by bonding both disks together. In this case, the highly reflective dielectric coating of the active disk can be directly cooled via water impingement. This method gives the lowest temperatures in the active disk; in addition, ASE is minimized (Jochen Speiser's article in this issue), but the optical distortion is much higher compared to the other mounting techniques due to the high temperature inside the undoped material on top of the active disk.[52–54]

3.3. New pumping schemes

One drawback of the experiments described above is the low operating temperature of the laser disk. The cooling fluid temperature was between 200 K and 220 K for demonstrating high optical efficiency. At room temperature, efficiency was reduced to values between 35% and 45%. Modeling[11,12,14,15] showed that efficiency could be increased by reducing the cooling fluid temperature, as well as by increasing the number of pump beam passes through the disk.

Already in 1995, the first modeling results were published, and in 1997 and 1999, detailed data showing the advantage of increased number of pump passes through the disk were reported. The challenge then became one of how to realize a larger number of pump beam passes. First, the brightness of the laser diodes for pumping had to be increased, thus allowing a smaller solid angle for pumping so that more imaging mirrors were used. Fortunately, the power and the brightness of the pump laser diodes increased rapidly. The

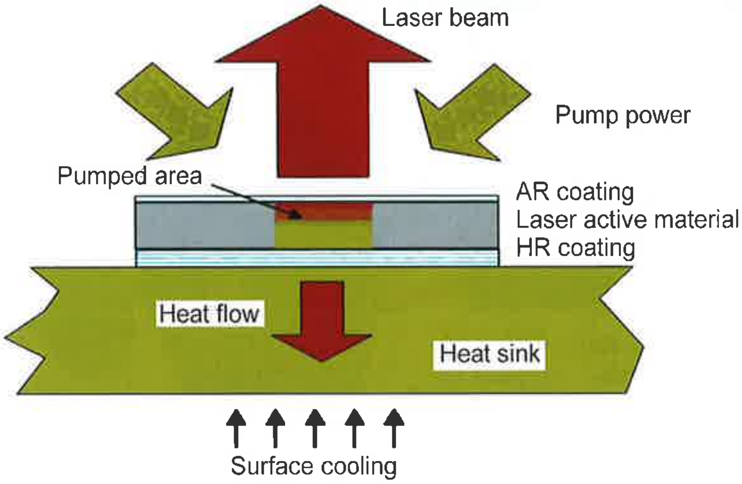

Fig. 6. Thin-disk laser design (courtesy of Dausinger and Giesen, GmbH).

objective then was to use relay imaging for the re-imaging process of multipass pumping instead of using a single spherical mirror. In 1998 the solution was found using a single parabolic mirror and some flat bending mirrors for realizing this multipass pumping.[20,21] Later an elegant solution was found for replacing all the bending mirrors with just four mirrors so that even 32 pump passes is quite easy. Immediately after these investigations were described in two patent applications, development began. In 1999, more than 57% optical efficiency was demonstrated for a high power disk laser operated at room temperature using 16 passes of the pump radiation. Today, 20 or 24 passes are used in most thin disk lasers, resulting in more than 60% optical efficiency at room temperature.

4. Thin-Disk Laser Design and Performance

4.1. Design principle

As explained above, the core concept is using a thin, disk-shaped active medium that is cooled through one of the flat faces; the cooled face is simultaneously used as the folding or end mirror of the resonator. This face cooling minimizes the transversal temperature gradient and phase distortions transversal to the direction of beam propagation. These features comprise the basis of the thin disk laser's excellent beam quality.

Figure 6 shows the thin-disk laser design principle. The laser crystal has a diameter of several millimeters (depending on output power/energy) and a thickness of 100 μm to 200 μm, depending on the active laser material, doping concentration, and pump design. The disk has a highly reflective coating on its back side for both the laser and the pump wavelengths, and an antireflective coating 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 very stiff fixation of the disk to the heat sink without disk deformation. To reduce the stress during and after the soldering process as much as possible, the heat sink is made from a heat expansion–matched material (CuW). The heat sink is water-cooled by impingement cooling using several nozzles inside the heat sink.

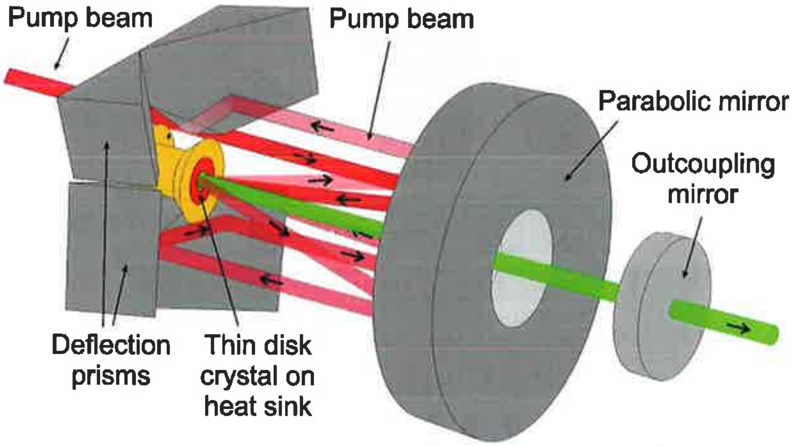

Fig. 7. Pump design of thin disk laser with 24 pump beam passes (picture courtesy of Institute of Laser Physics, University of Hamburg, Germany).

As mentioned before, the temperature gradients inside the laser crystal are mainly coaxial to the disk axis and the laser beam axis due to this mounting and cooling technique. 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 thermal lens effects and nonspherical parts of the profile of the refraction index 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 ignored for real-world 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 redirecting 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 Fig. 7. The radiation of the laser diodes for pumping the disk is first homogenized either by fiber coupling of the pump radiation or by focusing the pump radiation into a quartz rod. The end of either the fiber 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 redirected 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 reimaging can be repeated until all the (virtual) positions of the parabolic mirror were used. At the end the pump beam is

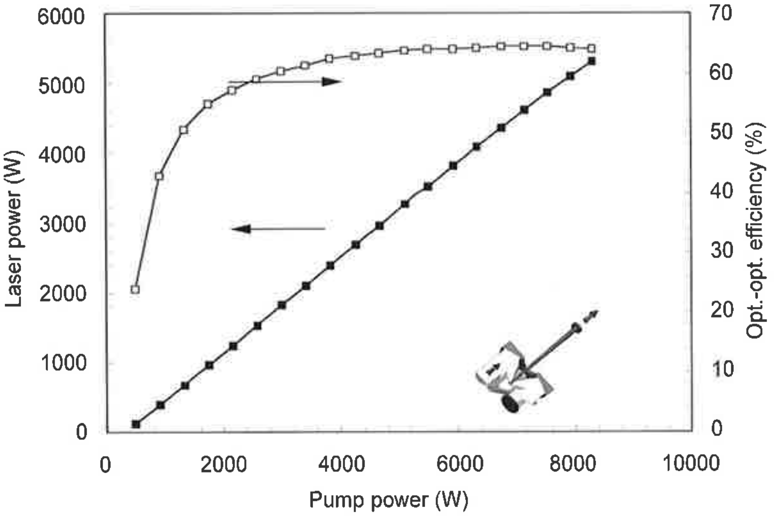

Fig. 8. Output power and optical efficiency from a single disk (courtesy of Trumpf-Laser).

redirected 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 were realized and more than 90% of the pump power is absorbed in the disk even for a disk thickness of much less than 200 μm.

Using multiple pump beam passes through the disk results in a thinner disk and/or a lower doping concentration, thus reducing thermal effects such as thermal lensing and stress in the disk. Another advantage is that the effective pump power density is increased (nearly 4 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., Yb:YAG) can also be used with this design.

Quasi-three-level materials offer the possibility to build lasers with high efficiency. They are, however, also difficult to operate because the energy difference between lower laser level and ground level is small, leading to a significant thermal population of the lower laser level. Some amount of pump power density is necessary just to reach transparency at the laser wavelength, making it necessary to pump the material with high pump power density for reaching threshold without excessively raising the maximum temperature of the crystal. 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 operating quasi-three-level systems at room temperature. 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 that 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.

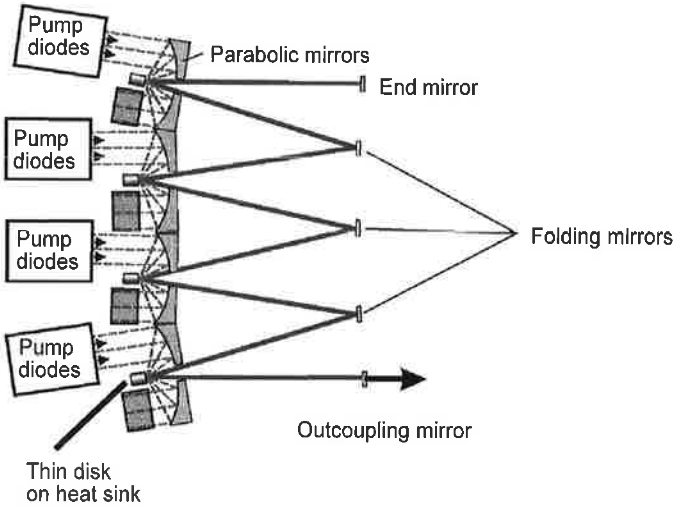

Fig. 9. Design of 16-kW thin disk laser using four disks (courtesy of Trumpf-Laser).

When operating the disk in this setup, 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 brightness of the pump laser diodes when increasing the disk laser power.

4.2. Thin disk laser in continuous-wave operation

Very high laser output power can be achieved from a single disk by increasing the pump spot diameter while keeping the pump power density constant. Fig. 8 shows output power from a single disk (Trumpf-Laser). More than 5.3 kW of power were achieved with a

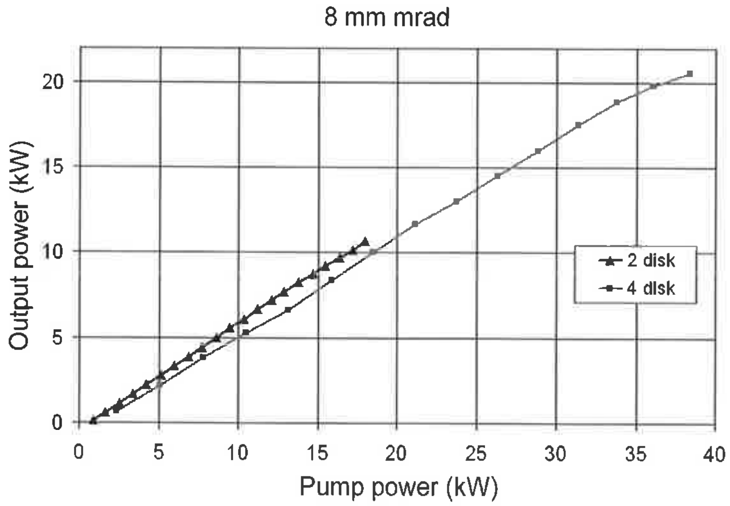

Fig. 10. Output characteristics of 8- and 16-kW lasers (courtesy of Trumpf-Laser).

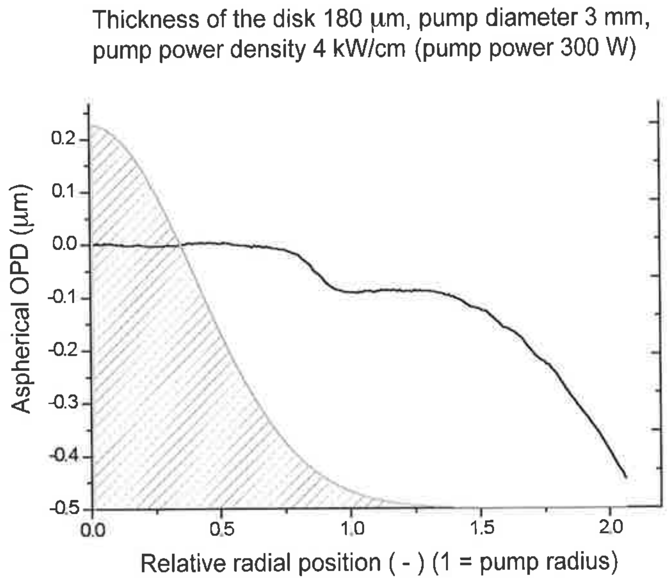
Thickness of the disk 180 μm, pump diameter 3 mm, pump power density 4 kW/cm (pump power 300 W)

Fig. 11. Nonspherical part of phase distortion and fundamental mode intensity distribution.

maximum optical efficiency of more than 65%. This high efficiency of the thin disk laser results also in very high electrical wall-plug efficiency of the total laser system, which is greater than 25% for industrial lasers with 16-kW output power and a beam propagation factor M^2 of less than 24.

Another way to scale the output power is the use of several disks in a single resonator. Fig. 9 shows the design of a 16-kW laser (Trumpf-Laser) where four disks are coupled together in one resonator, and Fig. 10 shows the output power of such a laser as a function of pump power. 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.

High-power industrial thin disk lasers in the kilowatt power range are typically operated with a beam propagation factor (beam quality) M^2 of about 10 to 20 (i.e., the focusability of the laser beam is 10 to 20 times worse compared to the theoretical limit $M^2 = 1$), which is sufficient for the typical demands of cutting or welding applications. Beyond this beam quality, the thin-disk laser design offers the possibility of operating high power lasers in the fundamental mode ($M^2 \approx 1$) due to small thermal effects and small optical distortions in the disk.[34,35] The optical distortions can be measured with an interferometer, and they can be separated into a nonspherical part and a spherical part that can be easily compensated by the resonator design. Fig. 11 shows the nonspherical part for a disk operated with 300 W of pump power.

Using a resonator design that has a stable fundamental mode diameter of 70% to 80% of the pump spot diameter, it is possible to achieve high laser output power with high optical efficiency. This relationship between pump spot diameter and fundamental mode size is an optimization vis-à-vis phase distortions and mode overlap. In Fig. 11, the measured nonspherical aberrations of the total optical phase distortions are shown demonstrating the low-phase distortions of the thin-disk laser design. The intensity distribution of a

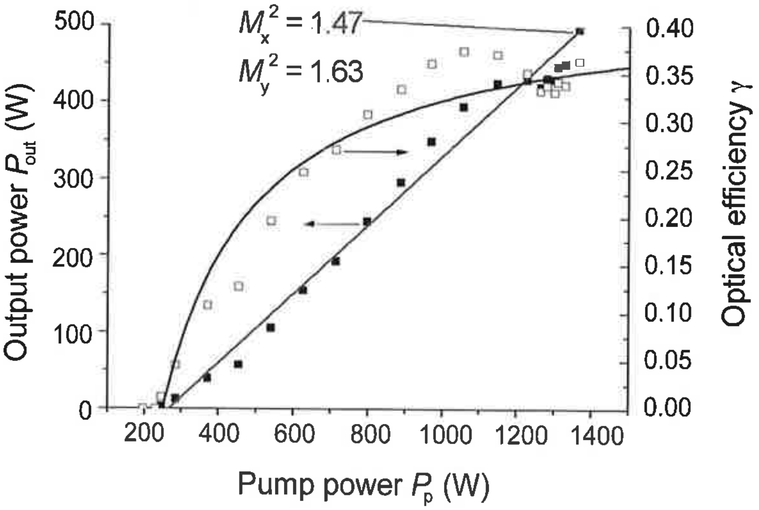

Fig. 12. Output power and optical efficiency for fundamental mode operation.

fundamental mode with a mode diameter of 80% of the pump spot diameter is sketched in Fig. 11 as well. For this mode, the phase distortions inside 2 times the mode diameter are smaller than 100 nm. Losses due to absorption in the unpumped region are simultaneously negligible, and higher modes are effectively suppressed by the absorption in the unpumped region ("gain aperture").

Figure 12 shows the results of a disk operated with 500-W laser power and a M^2 of about 1.6. The optical efficiency of this laser was higher than 35%. Even higher laser power levels with nearly fundamental mode properties will be possible in the future.

With the potential of very high output power levels for the fundamental mode, it is also possible to operate thin disk lasers in single-frequency operation. For achieving this, using a birefringent filter and one or two uncoated etalons inside the fundamental mode resonator are necessary. With such resonators, single-frequency power of up to 98 W was demonstrated.[24] 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.[6,23,33,57]

Another interesting feature is resonator internal doubling of the laser frequency for covering the visible spectral range with high efficiency. This was demonstrated successfully with various laser materials. With Yb:YAG, the wavelength tunability between 500 nm and 530 nm was shown with a maximum laser power of more than 50 W around 515 nm. For Nd:YVO$_4$, more than 12 W was demonstrated at the 532-nm wavelength and more than 3 W at 457 nm (doubling of the quasi-three-level transition at 914 nm). Also for Nd:YAG, more than 1 W at 660 nm was achieved when doubling the 1320-nm transition.

4.3. 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 required.

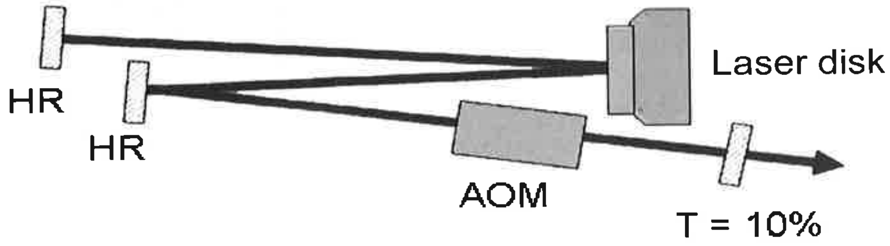

Fig. 13. Resonator design of q-switched laser.

As of this writing, pulsed thin-disk laser systems have been developed and demonstrated for the nano-, pico-, and femto-second pulse-duration regimes. All systems show excellent beam quality and high efficiency.[10,46,58]

In close collaboration with Ursula Keller's group at ETH Zurich, high average power femtosecond oscillators were developed. With the thin-disk laser design, it was demonstrated that the highest output powers are possible down to pulse durations of 240 fs.[1,9,29,49,55]

In the following sections, results for q-switched lasers, cavity-dumped lasers, and pulse laser amplifiers are discussed in more detail.

4.3.1. Q-switched operation of the thin disk laser. Figure 13 shows a resonator design for q-switched thin disk lasers. The resonator is folded so that a short resonator length is realized with a large mode area in the disk for fundamental mode operation. Q-switching is performed by a quartz acousto-optic modulator (AOM). Fig. 14 shows the pulse energy as a function of the repetition rate for Yb:YAG as the laser active material. Stable operation was achieved with repetition rates up to 13 kHz, while for higher repetition rates, bifurcations of the pulse energy were observed. The maximum pulse energy was 18 mJ at the 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 less than 2 in all cases.

Figure 15 shows pulse length as a function of the pulse repetition rate for various 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 the 13 kHz repetition rate. The reasons for these long pulses are resonator length (840 mm for fundamental mode operation) and relatively low gain per round trip of the disk, and hence relatively high reflectance of the outcoupling mirror.[31]

These restrictions in repetition rate and pulse duration (limited to pulse durations longer than 200 ns for the setup used) was overcome using cavity-dumped lasers (Section 4.3.2) or thin disk amplifiers, which are described in Section 4.3.3.

4.3.2. Cavity-dumped operation of thin disk laser. There are several means of extracting the energy stored inside a cavity. In the setup shown in Fig. 16, a thin film polarizer is used as the outcoupling mirror; the transmission is controlled by the voltage applied to the Pockels cell. An active control scheme—monitoring the intracavity power with a photodiode behind an HR mirror and controlling amplification time—is used to suppress instabilities at high repetition rates.

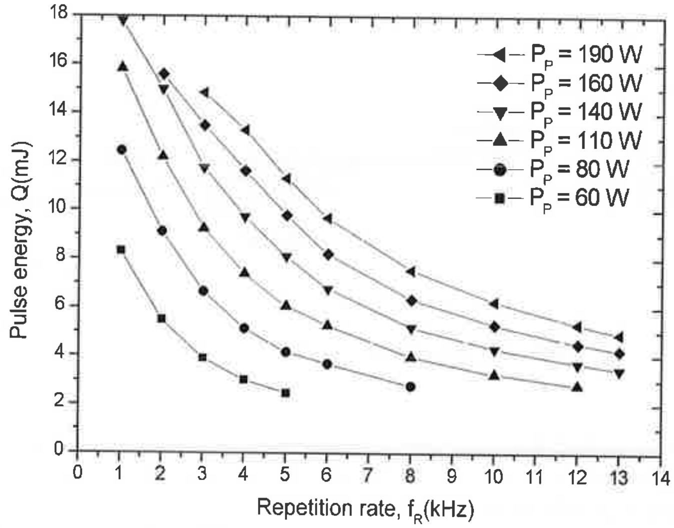

Fig. 14. Pulse energy of q-switched Yb:YAG thin disk laser as function of repetition rate for various pump power levels.

Applying the full quarter-wave voltage to the Pockels cell, the outcoupling can be switched to 100%, creating pulses up to tens of nanoseconds, depending on the round-trip time of the resonator. By applying only voltages lower than the quarter-wave voltage, one can reach a kind of "cavity leaking" instead of cavity dumping with longer pulses. In this case, the pulse duration and pulse energy can be controlled very precisely. This setup can also be used to generate 515-nm pulses by inserting a lithium triborate (LBO) crystal into

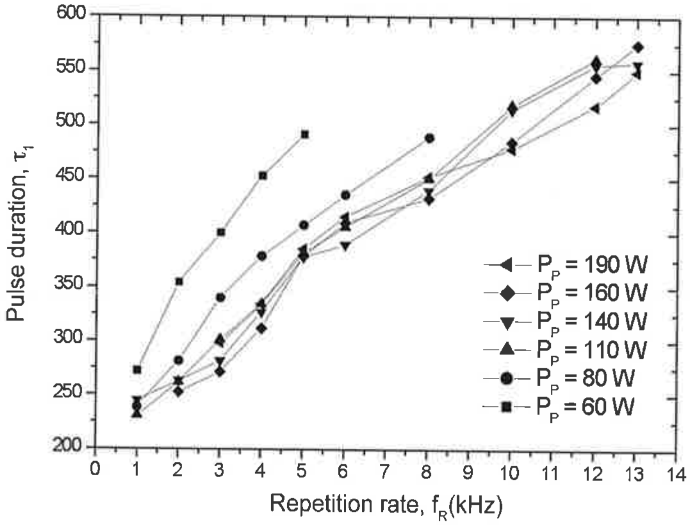

Fig. 15. Pulse duration of the q-switched pulses.

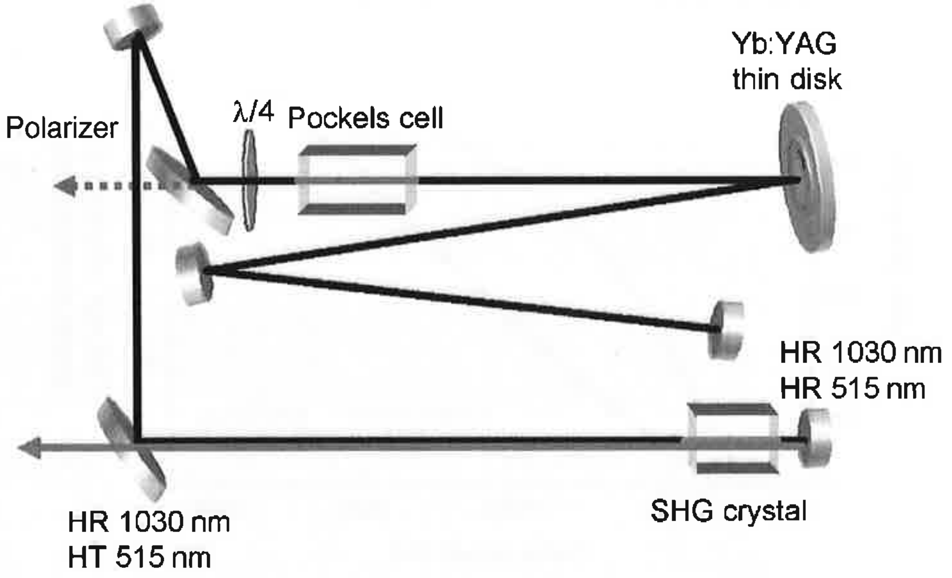

Fig. 16. Experimental setup for the cavity-dumped laser at 1030-nm lasing wavelength (used without doubling crystal) and with SHG at 515-nm wavelength.

the cavity as shown in Fig. 16. In this case, the IR energy inside the cavity is dumped to control the duration of the second harmonic pulse.

The maximum output power at a repetition rate of 100 kHz is 1.2 kW at the 1030-nm wavelength and 700 W at the 515-nm wavelength with a pulse duration of 350 ns (Fig. 17). An advantage of the system is the tunability of the pulse duration, which can be influenced during and after amplification by the quarter-wave plate and the voltage at the Pockels cell, respectively. We were able to tune the pulse duration from 200 ns to 800 ns in a similar laser with 100 W of output power.

4.3.3. Amplification of nanosecond, picosecond, and femtosecond pulses. In order to produce shorter pulses with high pulse energy, a setup consisting of a master oscillator followed by a regenerative amplifier was used. The schemata of such setup is shown in Fig. 18. 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 pulses with the right wavelength and a pulse duration shorter than the round-trip time of the amplifier resonator.

For amplifying picosecond or femtosecond 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 thin film polarizer as the pulse picker for reducing the repetition rate to the desired frequency.

The key components of the regenerative amplifier are the disk as amplifying medium, and the thin film polarizer in combination with the Pockels cell as the polarization switch for switching in and out of the seed pulses and the amplified pulses. Additionally, for amplifying

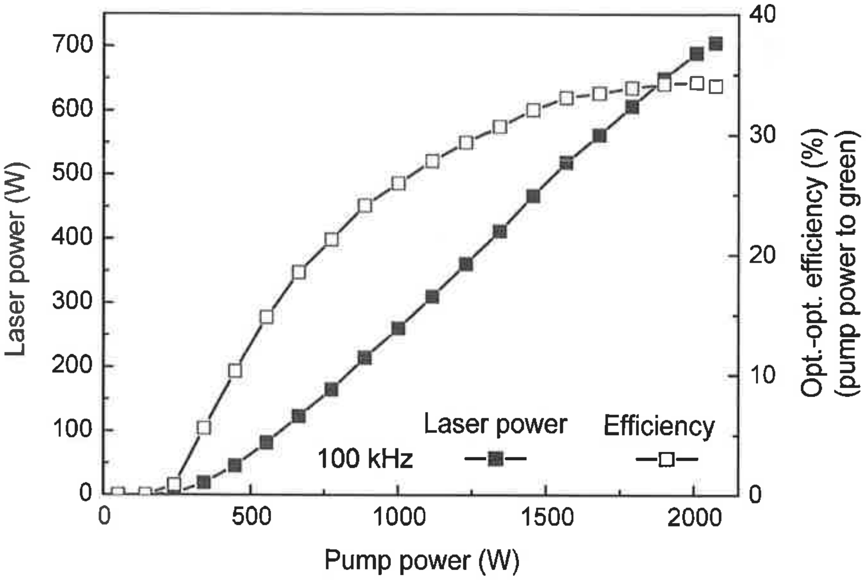

Fig. 17. Output power for cavity-dumped laser with intracavity SHG (courtesy of Trumpf-Laser).

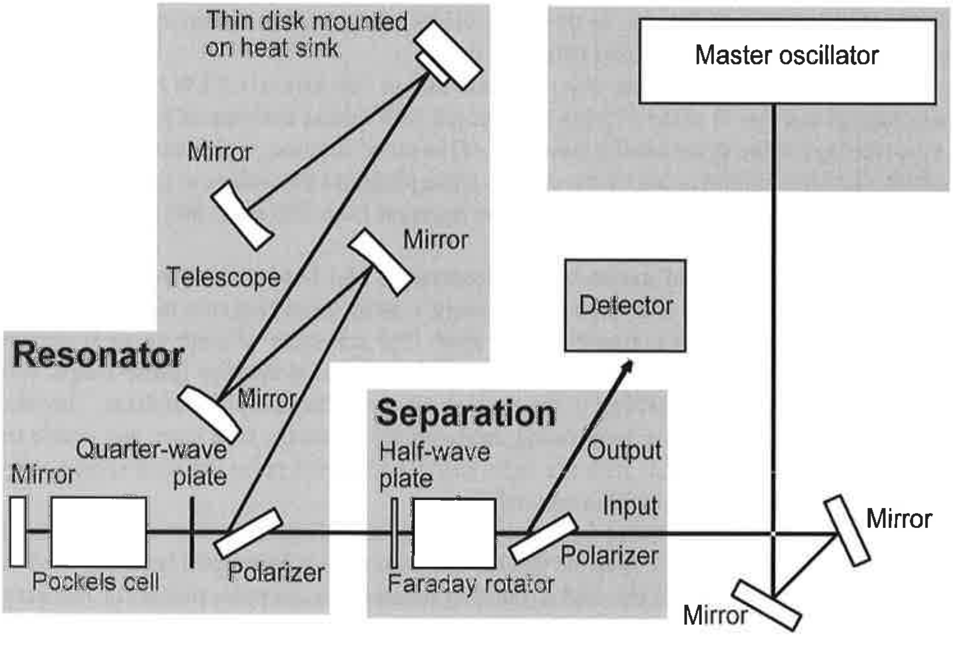

Fig. 18. Schematic setup of an oscillator-amplifier system for pulse generation and amplification.

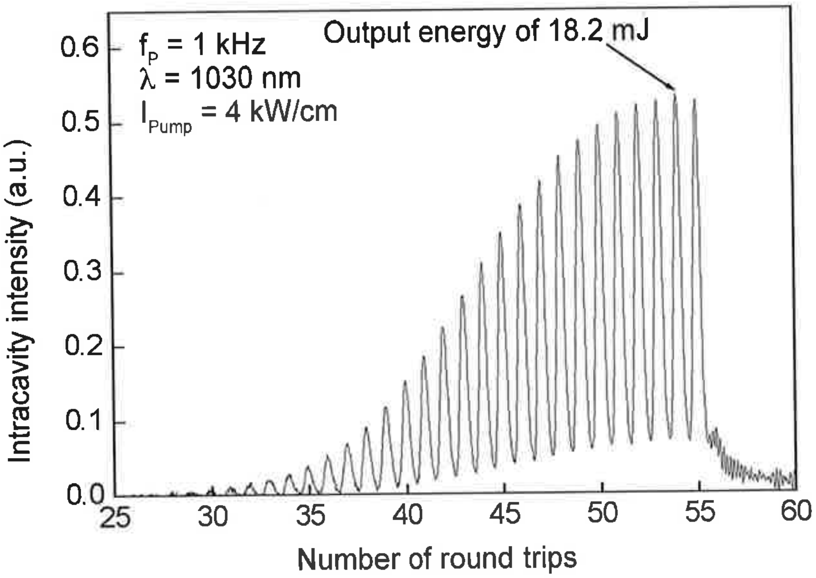

Fig. 19. Pulse build-up inside regenerative amplifier.

femtosecond 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 a single round trip of the pulses inside the resonator.

Because of the small gain of the thin disk in the amplifier (10% to 40% per round trip, depending on the operational conditions), the pulses need between 50 and 200 amplifying round trips 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, efficiency can be dramatically reduced.

Using an oscillator with nanosecond pulse duration, the maximum energy extracted thus far is more than 300 mJ with a repetition rate of 100 Hz and a beam propagation factor of $M^2 < 1.3$. Fig. 19 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 (18 mJ of energy, 1 kHz repetition rate) in these experiments. According to the scaling laws, increasing the pumped area and the mode diameter while keeping the energy density constant can increase the energy further.

Using a picosecond oscillator (pulse duration 1.8 ps) as the seed laser in another setup allows the amplification of picosecond pulses up to nearly 5 mJ of energy at 1 kHz repetition rate and up to 1 mJ at 20 kHz. Due to gain narrowing in the amplifier, the pulse duration of the amplified pulses is extended to 4 ps. The beam quality for these pulses is also nearly diffraction limited.[27,28,30,44,45,47,56]

Wolfgang Sandner and his coworkers at the Max-Born Institute in Berlin achieved nearly 500 mJ of pulse energy for a picosecond-pulse, chirped pulse amplification (CPA) system at a 100-Hz repetition rate. In this case, the pulses were stretched to nearly 1 ns duration and compressed after amplification.

Using higher repetition rates in another experiment, about 0.3 mJ at a repetition rate of 200 kHz was demonstrated. The average laser power is approximately independent of the repetition rate at such high repetition rates.

In another experiment, Yb:KYW was used as laser active medium.[43] 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, GTI mirrors were used for keeping the pulses short during the amplification. An Yb:glass oscillator as seed laser–delivered pulses with a pulse length of about 500 fs and energy of about 1 nJ. These pulses were amplified up to more than 100 μJ with a pulse duration of less than 900 fs at a 45-kHz repetition rate.[3–5] It is remarkable that this result was achieved without CPA. Due to the large beam diameter inside the amplifier (2 mm in the Pockels cell), the pulse stretching by nonlinear effects was limited to pulse duration values below 1 ps.

Using seed pulses with a duration of 270 fs and no compensation of the increasing pulse duration in the amplifier, but compressing the pulses after amplification with a grating compressor, a pulse length of 250 fs was demonstrated at an output energy of 116 μJ and at a repetition rate of 40 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 energies for all pulse durations between 100 fs and several microseconds.

4.4. Possible thin-disk laser 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 and the lifetime of the excited state is not too short. The first material used with the thin disk laser was Yb:YAG, and with this material most of the high power or high energy results are achieved. Yb^{3+} has two important benefits: a small quantum defect and no parasitic effects such as upconversion, cross-relaxation, excited-state absorption, and so on, but it is a quasi-three-level material. Laser operation of Yb^{3+} with the thin disk laser was demonstrated in a large variety of host materials, including Sc_2O_3, Lu_2O_3, KGW, KYW, $LuVO_4$, YVO_4, and $NaGd(WO_4)_2$.[40,50]

Other active ions were also successfully operated in the thin-disk laser setup: thulium in YAG,[2,19] holmium in YAG,[51] and neodymium in YAG[25,32] and YVO_4.[22,36–38] Laser activity of Cr^{2+}:ZnSe has also been demonstrated.

With neodymium-doped materials, not only the four-level transitions were used, but also the quasi-three-level transitions, resulting in 5.8-W laser power at 914 nm with Nd:YVO_4 and 25-W laser power at 938 nm and 946 nm with Nd:YAG.

Upon applying the thin-disk laser design to semiconductor structures (e.g., quantum well structures), it is possible to adapt the laser wavelength to demands of the application because quantum well structures can be designed to the desired wavelength (today in the range of 400 nm to 2700 nm), whereas solid-state laser materials are limited to the spectral range that is given by the laser active material.[8]

For reducing the waste heat in semiconductor devices further, we demonstrated the possibility of pumping directly into the quantum wells using a wavelength that is less than 5% shorter than the laser wavelength.[48] In this way, it is possible to reduce the waste heat and the temperature in the structures so that such structures can in principle be operated with higher efficiency and also at higher temperatures. In addition, scalability to higher power levels is easier, since the increase of the pump spot is not so sensitive to the waste heat flux conditions. The disadvantage of very low absorption when pumping directly into the quantum wells can then be overcome by using the multipass pump design similar to that for solid-state thin disk lasers.

5. Government support

The first real-world industrial applications of lasers began in the 1970s. In addition, the first high power lasers became available for materials processing. Consequently, the first institutes started working in this field, as did BMFT in supporting and funding private companies and institutes. In the early years, private-sector or institute projects were funded separately. But very soon it became obvious that collaboration between companies and institutes could increase the efficiency of such projects. In the 1980s, large-scale collaborations between German companies and laser institutes were launched. The goal was not to develop products but designs; test procedures and results were used by all partners. In this way, the knowledge and experience of many partners were brought together.

Another important aspect of such collaborations was private sector interest in the work of the institutes. This interest had to be expressed by the companies, and substantiated by contributing to institute project financing (usually 25%). The other 75% for the institutes came from the BMFT. In this way, it was guaranteed that industry had a real interest in the work of the institutes. Private sector projects were then funded to about 50%. With this model, it was possible for institutes to receive funding for projects of interest to the private sector. Moreover, great interest and commitment by company stakeholders were ensured because only a half of company costs were covered by the BMFT.

This model was developed and improved during the 1980s. When thin-disk laser development began, such collaborations for developing diode-pumped solid-state lasers already existed. All the big German laser companies were involved in such collaborations. Consequently, it was quite easy to gain interest and participation by a number of companies in developing our ideas.

The next important point was that the person in the ministry (Dr. Rainer Röhrig) responsible for all such laser projects in Germany was very enthusiastic about lasers in industrial applications. Over the years, he was able to increase BMFT financial support for laser projects such that many large-scale laser projects were supported. Röhrig believed that laser technology for industrial applications was a very important technology for the future, especially for Germany and the German laser industry. Today, it is clear how right he was. German laser companies today are world leaders in respective fields, and this would not have been possible without Röhrig's support and commitment.

Consequently, Röhrig was also highly interested in thin disk lasers, not only from the ministry's perspective, but also from the technical side. His interest in technical details and his leadership abilities and commitments helped to push the German laser industry to innovative excellence.

6. Patents and Licensing Policy

In spring 1992, after developing details of the thin-disk laser design, the University of Stuttgart and the DLR decided to apply for a patent encompassing all the new ideas. At this time, it was decided also to postpone patent application until the laser principle was successfully demonstrated. After studying the prospects of Yb:YAG in the first experiments in late December 1992, discussions about a thin-disk laser patent with our patent attorney Jürgen Beck began. The patent application was discussed until June 1993 when a final draft was sent to the German patent office.[7]

Immediately after publishing the first results in 1994, Daniel Guillot of the French company Nanolase asked for a license for his company again and again. Therefore, in 1995 initial discussions began with the German laser companies about conditions for licensing the thin-disk laser design. In 1996, a meeting took place in Stuttgart attended by representatives of all the German laser companies, VDI-TZ (in turn representing the BMFT), our patent attorney, and people from IFSW and DLR-TP. The BMFT had asked that German companies requesting a license be given preference since the entire thin-disk laser development effort had been funded by BMFT. At the end of the day, it was agreed that licenses should be given first to German companies only until the major German companies began marketing their thin-disk laser products. Another condition accepted at the time was that a license request by a foreign company would be approved only if all the German licensees agreed. These rules were in force until 2003 when BMFT encouraged IFSW and DLR to sell licenses worldwide to as many companies as possible.

Shortly after the meeting in 1996, the first companies signed the license agreement. Trumpf, Jenoptik, and Rofin-Sinar were the first to sign, and as of this writing, 25 companies had signed licensing agreements.

Later, the IFSW (University of Stuttgart) applied for an additional four patents. The most important one deals with the parabolic mirror and the relay imaging optics for the pump power. The next important patent covers the technique of replacing all the bending mirrors of the pump optics by just four mirrors independent of the number of pump beam passes through the disk. All the companies that had already entered the market with thin disk lasers also purchased licenses for these patents.

The thin-disk laser patents and the patent policy supported the German companies in developing and selling thin disk lasers. This policy helped also to further develop thin-disk laser technology in Germany and in German companies.

7. Industrial Applications

As discussed above, development work took place in a collaborative project between German companies and institutes since December 1992. The goals for this and successive projects were the development and evaluation of various concepts for diode-pumped solid-state lasers. In addition, Trumpf-Laser (formerly Haas-Laser), Rofin-Sinar, and Jenoptik were project partners. Therefore, these companies learned all the details about thin-disk laser development during internal project meetings several times a year. When power scaling of the thin disk laser had been successfully demonstrated, increasing attention from these companies was directed at the institutes. All three companies initiated their own thin-disk laser development. After demonstrating more than 220 W of power from a single disk in late 1996 (this result was published in 1997), the possibility of building high-power, diode-pumped, solid-state lasers using the thin-disk laser design became clear.

At this time, Hans Klingel of Trumpf was responsible for the solid-state laser part of the company. He and Paul Seiler, CEO of Haas-Laser (today Trumpf-Laser), were major boosters for thin-disk laser development. In addition, some IFSW doctoral candidates

Fig. 20. Ten-watt, cw, diode-pumped, diffraction-limited, thin-disk ND:YVO4 laser (courtesy of Jenoptik).

(Andreas Voss, and later Christian Schmitz and Martin Huonker) who were working on thin disk lasers joined Trumpf-Laser to support its development program.

While Trumpf-Laser and Rofin-Sinar started working on high-power (kilowatt-class) thin disk lasers for materials processing, Jenoptik concentrated its efforts on low-power (<100 W) thin disk lasers for medical applications and low-power materials processing applications such as marking. Jenoptik showed the first industrial thin-disk laser product at the 1997 Laser Fair in Munich. In the same year, Jenoptik marketed the first thin disk lasers.

The first Jenoptik product was a diode-pumped, Nd:YVO_4 thin-disk laser with 10-W output power and a M^2 less than 1.3 (Fig. 20). On the basis of this first laser, Jenoptik developed a frequency-doubled version especially for medical applications (eye surgery), which has been a great market success. As of this writing, Jenoptik had sold more than 11,000 thin disk lasers in diverse market segments (cw, pulsed, IR, and green).

In 1999, Nanolase was the second company to enter the thin-disk laser market; Beck Lasertechnik and ELS followed in 2000 with their thin-disk laser products. All of these small companies tried to find a market for their low-power thin disk lasers. However, market conditions for such small-scale enterprises were quite difficult; these companies either disappeared or were bought out by larger companies.

In the meantime, Trumpf and Rofin-Sinar developed their high-power thin disk lasers, and during the 1999 Laser Fair in Munich, Trumpf showed a 1-kW thin disk laser in operation. Trumpf used two disks in one resonator for achieving 1 kW of output power. The beam quality was so good that the power was coupled into a fiber with a 50-µm diameter

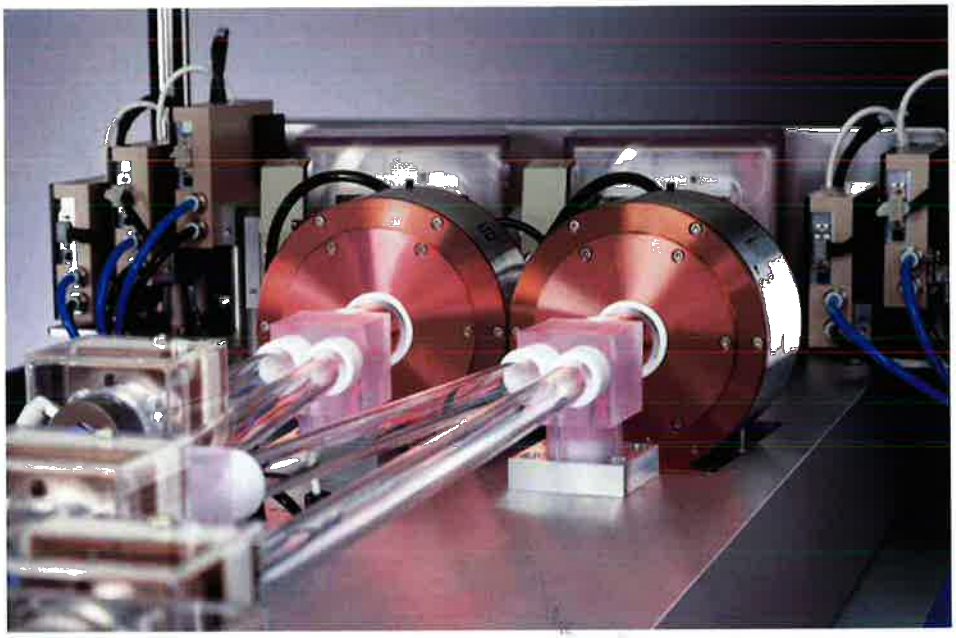

Fig. 21. One-kilowatt, thin disk laser for materials processing (courtesy of Trumpf-Laser).

and a numerical aperture (N.A.) of 0.2. In 2001, Trumpf announced the first commercial, high-power thin disk laser with 1 kW of output power (Fig. 21), and in the same year the company started selling high power thin disk lasers. Rofin-Sinar followed 1 year later with its pulsed, high-power thin disk lasers. As of this writing, Trumpf-Laser had sold more than 700 thin disk lasers with an output power of 1 kW or more. Up to 16-kW thin-disk laser power is available today for industrial applications.

These examples show that the thin-disk laser principle has successfully found its way from the laboratory to real-world applications in industry. In a very short time after the very first ideas were developed and modeled, the design was used by many companies. More companies will follow suit in the near future.

8. Summary and Outlook

All outcomes discussed in this article demonstrate the potential of the thin-disk laser design for high power lasers. In addition, results presented by other researchers and contributors to this journal issue support this statement. Thin disk lasers are easy to build and to operate. The simple scaling laws of thin-disk laser design and easy adaptation to many laser active materials will push implementation this design in numerous applications.

The innovative thin-disk laser concept allows construction of diode-pumped solid-state lasers with very high output power, efficiency, and beam quality. This design can be used to build nearly all operational modes of solid-state lasers such as cw pulsed operation with pulse duration between femtoseconds and microseconds and laser amplifiers, and with superior properties compared to other designs.

In future, new materials will be investigated with the goal of further enhancing power, energy, and beam quality. Laser output powers of more than 100 kW and energies of more than 10 J will be possible. New materials will create markets for new wavelengths, and customized lasers for specific markets will become feasible with the semiconductor thin disk laser.

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