Present Status and Future Prospects of High Power Diode and Diode-Pumped Solid-State-Laser Technology and Applications in Germany

Friedrich Bachmann, ROFIN-SINAR Laser GmbH, Mainz, Germany*)

Product Manager Diode Lasers & MDS Project Manager

High power diodes are entering the laser materials processing market in two different laser types: as an extension of traditional laser processing in form of the diode pumped solid state lasers and in a really new and exciting form as high power diode laser systems up to several kilowatt for direct processing. In this article we describe the basic technology of high power diode lasers as well as their use in high power solid state lasers and for direct applications. Some applications, which have already found their way to the industrial manufacturing will be described. A leading role of German industry in these technologies, i.e. laser development as well as their application in new fields shall be assured by laser related national projects; some of them are described in this article as well.

1. Introduction

Laser action in GaAs or GaAsP laser diodes at cryogenic temperatures has been demonstrated as early as 1962 [1, 2, 3] and a few years later at room temperature in AlGaAs/GaAs double-heterostructures [4,5]. At this time, however, certainly nobody had the vision, that these lasers could ever play an important role in laser materials processing, since they provided only low power for a short time and for a high price. However, caused by successful investigation of the crystalline structures, by detailed understanding of the failure mechanisms, by considerable improvement of the manufacturing processes, laser diodes entered successfully the communication, consumer electronic and computer markets at an incredibly high volume: the total diode laser market in 1999 has been 3,17 Billion US$ [6, 7]; in fact, 2/3 of the entire laser market today is covered from diode lasers. From this high number, however, only 1.7% (53,6 Mio.$) are used for pumping modules and only 0.5% (16,7 Mio.$) are used for direct materials processing. Also, today only 3,4% of the total materials processing laser market (1,113 Bio. $) are diode pumped solid-state lasers and 1,5% are diode lasers for direct applications. Nevertheless, because of their unique features, e.g. small size and low weight, which makes them easy to integrate and high efficiency and reliability, which leads to low running costs, diode lasers gained extremely high interest as a pump source for solid-state lasers as well as as a light source for materials processing.

2. Laser Systems

High power diode systems and diode pumped solid state lasers take advantage of the unique features of the basic diode lasers as mentioned above: they are very efficient and extremely small. Using special combination concepts low power diode elements can be combined either to high power pumping modules or to efficient high power materials processing sources.

2.1 Diode Laser Technology

From a single diode laser element only a few milliwatts can be extracted from the pn-transition; such elements are e.g. used for communication or in CD-ROM's, but the power is of course by far not sufficient for high power applications. Many of such basic units are therefore integrated in one semiconductor element, which is called a laser bar. A laser bar (see fig. 1) has a size of ca. 10000 x 1000 x 115 µm³, where 1000 µm is today a typical resonator length. The special way how the light is generated in the pn-transition leads to emission characteristics, which are unusual for a laser: the emission shows a large divergence from a very narrow slit in the direction of the pn-transition ("fast-axis") and a smaller divergence but a wide emitting stripe in the plane of the pn-transition ("slow-axis"), as schematically shown in fig.2.

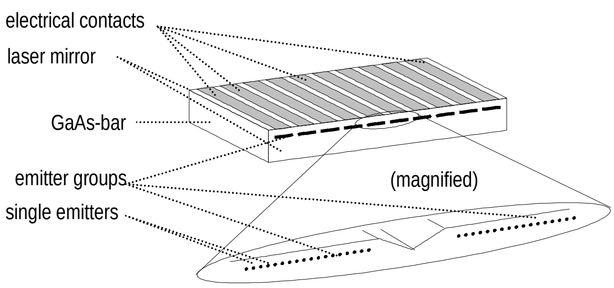

Fig.1: Scheme of a diode laser bar

*) Address: ROFIN-SINAR Laser GmbH, Galileo-Galilei-Str. 10, D-55129 Mainz,
Tel. +49 (6131) 9226-28, Fax. +49 (6131) 9226-57, e-mail: f_bachmann@compuserve.com

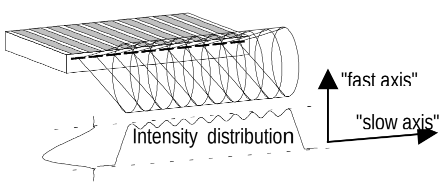

Fig.2: Scheme of emission and intensity distribution of a diode laser bar

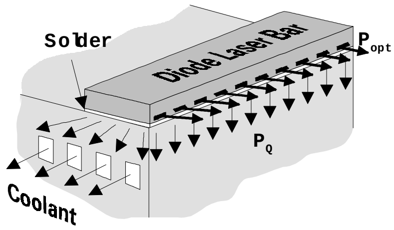

Fig.3: Scheme of a heat sink with a mounted (soldered) laser bar

Even if the electro-optical efficiency ($\eta_{e\text{-}o} = P_{opt}/P_{el} = P_{opt}/(P_{opt}+P_Q)$) is in the range of 40 to 50% or even more, reasonable amount of heat has to be cooled away if the power shall be increased without damage of the semiconductor itself or the mirror facets. Therefore the semiconductor bar is mounted onto special water-cooled heat sinks (fig.3), what finally allows to drive currents as high as 50 or 60 A through the semiconductor element; this results in a laser power of 40 to 50 W per bar.

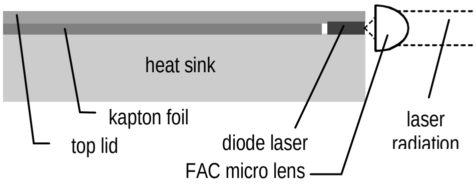

Fig.4: Fast-axis collimation (FAC) by cylindrical lens (schematically, side view)

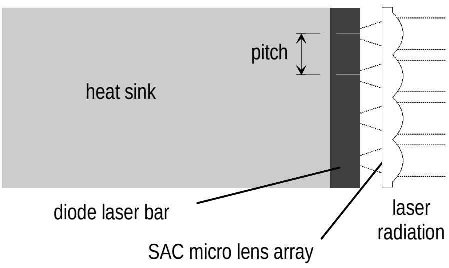

Fig.5: Slow-axis collimation (SAC) by microlens array (schematically, top view)

The large divergence in the direction of the pn-transition ("fast-axis") can be compensated by use of - normally aspheric - cylindrical lenses, so that almost parallel light is provided from the laser bar in this axis (see fig. 4). A collimation of the "slow-axis" can be performed by use of micro-lens arrays, as schematically shown in fig.5. For geometrical reasons it is evident, that the distance of the emitter areas must have a distance ("pitch") which is large enough so that the collimation takes place before the radiation of the individual emitter areas is overlapping. However, more complex solutions are provided for smaller pitch, which basically deflect the adjacent emitter areas by micro-prisms or mirrors into different planes and making them parallel again by another set of prisms, so that overlap is avoided in the emission plane and slow axis collimation is nevertheless possible [8, 9, 10, 11].

These basic elements consisting of laser bar, cooling unit and - if necessary - micro-optics, can be stacked on top of each other; from one stack with about 30 stacked units up to 1,5 kW can be extracted (fig.6). Further increase of output power (under the condition, that beam quality is maintained) can be achieved, if those stacks are combined in such a way, that the free areas in the aperture of one stack are filled in by one or two others, as schematically shown in fig.7: The radiation "lines" of stack 1 and 3 are bent at prisms, radiation of stack 2 is transmitted through a gap in the prism stack, so that finally all three stacks radiate into the same area. It must be mentioned, that – as shown in the figures - high power diode lasers are not single lasers but consist of incoherent coupling of several individual low power laser sources. This must be considered, if optical systems, beam quality etc. are discussed!

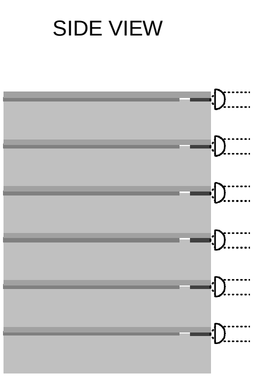

Fig.6: Scheme of 6 stacked diode lasers

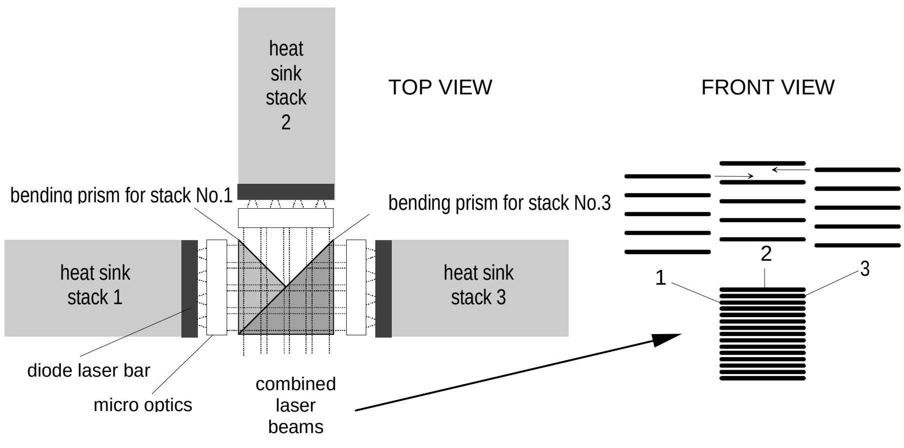

Fig.7: Combination of three diode laser stacks by aperture fill. Left: Top view – bending of the radiation at prism stack. Right: Front view - scheme of the emission lines

Furthermore, single or combined stacks can be coupled into the same optical path by polarization coupling and by coupling of different wavelengths. In case of polarization coupling the fact is used, that under certain circumstances the light from the semiconductor laser bar is linearly polarized. Using a half wave plate polarization plane is turned by 90°, so that two bars, stacks or multiple-stacks can be combined by a polarization filter (fig.8). Wavelength coupling (fig.9) makes use of the possibility to have diode laser bars available basically for arbitrary wavelength over a reasonable range. In reality, however, it is necessary to develop a stable manufacturing process for each individual wavelength to produce reliable bars with high yield and long lifetime; that's why nevertheless only few characteristic wavelengths are available for industrial lasers. From the point of view of materials processing, this combination method is acceptable, since most processes do not depend critically from wavelength in this wavelength range.

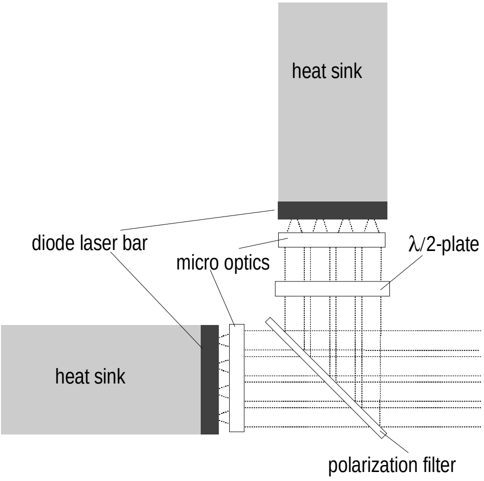

Fig.8: Combination of diodelasers resp. diode laser stacks by polarization coupling

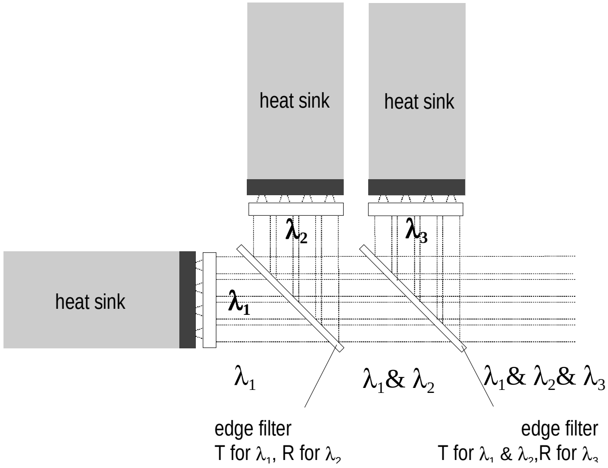

Fig.9: Combination of diode lasers stacks by wavelength coupling (T = transmitting; R = reflecting)

It is common to all combination methods, which are mentioned above, that the radiation of the stacks is coupled into the same optical path; i.e. the coupling does not only generate higher power (which would be very simple with diode lasers), but the power is increased by – theoretically – maintaining the beam quality, which finally means increasing the power density resp. brilliance. Using such combination methods today up to 8 kW laser power can be generated in a laser head, which is not much bigger than a shoe box; average power densities of up to 5×10^5 W/cm² can be achieved.

For further improvement of the beam quality and for adapting the different beam qualities in the fast and the slow axis sophisticated beam rearrangement concepts are necessary, e.g. the step mirror [10, 11] or the beam tilt unit [9]. Such special optical elements cut the wide slow axis of the laser beam in smaller pieces and re-arrange them in different planes on top of each other, so that finally the beam quality in one (the slow) axis is improved at the expense of the other (the fast), so that they are roughly matched. This is especially important for coupling of the diode laser radiation into optical fibers.

2.2 High Power Diode Laser Systems

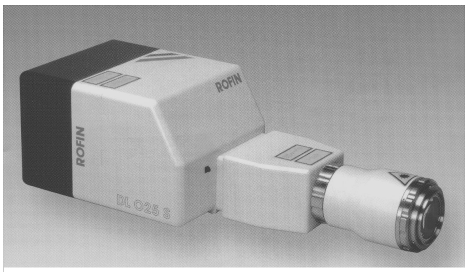

Fig.10: Typical high power diode laser head for materials processing (ROFIN DL025S, 2.5 kW)

Using the cooling-, mounting-, beam-forming- and coupling-technologies mentioned in 2.1, high power diode systems up to several kW can be made. An example is shown in fig. 10; the picture shows a 2.5 kW diode laser system. The size of the laser head shown is just 580 mm (including the optics) x 180 mm x 155 mm and the weight is only 15 kg. Of course, power supply and chiller have to be added; however, because of the high efficiency they are much smaller than those for conventional lasers. The system produces a 1,3 mm x 1,3 mm square focus (1/e²-criterion) at a working distance of 42 mm (f=63 mm) which can be enlarged by use of special optics. Because of this improved beam quality, these units can even be used with an optical fibre. The coupling unit (fig. 11) can be easily mounted in front of the head; the laser power is then delivered to a working head by a 1,5 mm diam., 0,35 N.A. optical fiber. The beam profile of a high power diode laser show typically a rectangular shape with a top hat profile in one direction and a Gaussian in the other (fig. 12a); if a fibre is used, a very high quality circular top had profile (fig. 12b) can be provided.

Fig.11: Fiber coupling module for ROFIN DL-S series (e.g. the laser shown in fig. 10)

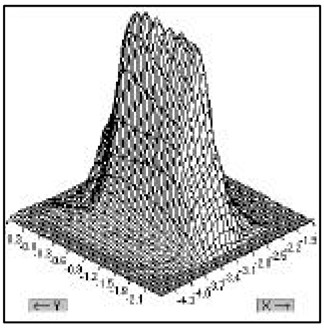

Fig. 12a: typical energy distribution in the focal plane of a standard high power diode laser

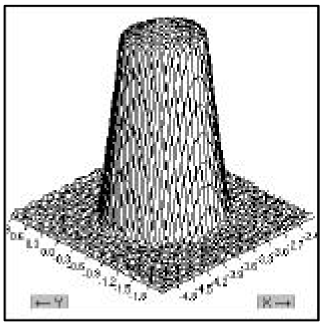

Fig.12b: typical energy distribution in the focal plane of a fibre coupled high power diode laser

2.3 Diode Pumped High Power Solid-State-Lasers [1)]

Diode laser packages as shown in fig. 6 or in similar configurations find an important application in the use as pump sources for high power solid state lasers. Rather short life of the excitation lamps in conventional Nd:YAG lasers demanded a solution to reduce down time in manufacturing. Furthermore, the diode laser wavelength can be tuned by the manufacturing process to a wavelength, where absorption of the laser material is maximal. This reduces on one hand the thermal load to the active material (i.e. the thermal lens effect) and increases efficiency on the other. Thus, compared to conventional lamp pumped Nd:YAG lasers, diode pumped high power solid-state lasers provide improved beam quality at a higher efficiency. In fact, a beam parameter product[2)] of 12 mm mrad[3)] can be achieved with a high power system shown in fig. 13a. It is a side pumped rod type laser with 8 chambers and has an output power of 4.4 kW at an overall wall plug efficiency of >7% [3)]. In fig.13b a 2.2 kW laser with the opened hood is shown and the 4 modular laser chambers can be easily recognised.

Fig.13a (left): 4.4 kW diode pumped NdYAG-laser (ROFIN DY044)

Fig. 13b (right): 2.2 kW diode pumped NdYAG laser with open hood

A very new and clever concept of solid state laser, the so called "thin disk-laser" has been proposed from Giesen et. al. [14] several years ago: A thin Ytterbium doped disk, mounted on a heat sink, which also acts as a resonator mirror, is intensively pumped with 940 nm diode lasers. Since the disk is cooled homogeneously from the rear side, there is almost no thermal gradient in radial direction, which means, that thermal lensing effect is almost completely eliminated. Thus, as a consequence, the diode pumped solid state disk laser provides a very high beam quality. Fig. 14a shows the principle of the disk laser whereas fig 14b represents a photograph of the experimental set-up. So far more that 600 W with a beam quality of 5 mm mrad have been reached out of one disk at an optical-to-optical efficiency of 48%; even more than 1 kW has been reached with lower beam quality.

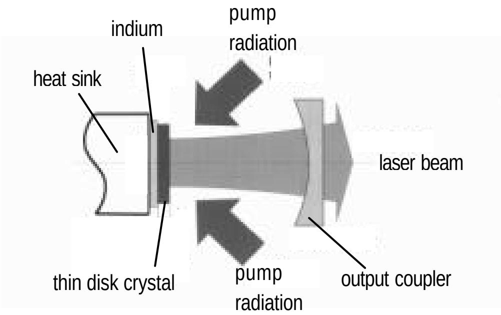

Fig.14a: Prinziple of disk laser

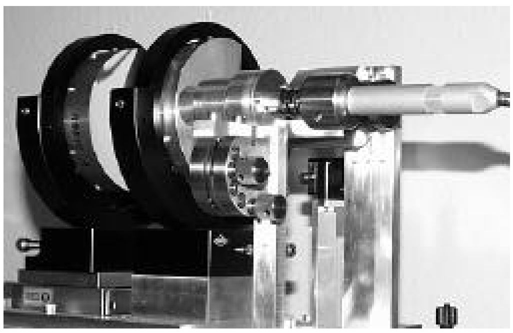

Fig.14b: Experimental set-up of disk laser

1) for more details see [12, 13]

2) defined as half beam waist diameter (w_0) x half divergence angle (θ_0): BPP = $w_0 * \theta_0$

2.4 Comparison of Different Laser Types

From applications point of view, among others beam quality and power define the possibilities and the application areas. Therefore, based on an earlier proposal of P.Loosen [15] beam quality (beam parameter product[2)]) is shown versus output power for diode lasers, different types of solid state lasers and CO_2 lasers in fig. 15. The wide band of typical beam qualities for diode lasers[1)] is based on data for direct diode as well as for fibre coupled diode lasers; it reflects the wide range of lasers, which are available on the marketplace today [13]. The graph also very clearly demonstrates the inferior beam quality of today's diode laser systems compared to the established CO_2 and Nd:YAG lasers; this is of course a consequence of the incoherent coupling of the many lasers in a bar resp. in a diode laser stack, as described in sect. 2.1.

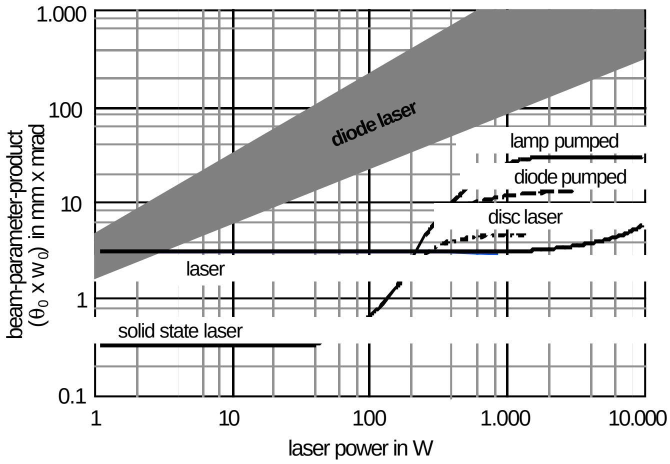

Fig.15: Beam quality (beam parameter product) as a function of laser power for diode lasers in comparison with conventional CO_2 and solid state lasers (after [15])

3. Industrial Materials Processing Applications

As a consequence of the rather poor beam quality in the high power range traditional laser applications such as cutting and high speed deep penetration welding are not yet available as a market for high power diode lasers (even if deep penetration welding has been demonstrated recently [16]). However, as can be easily see from fig.16, where typical requirements for power and beam quality are presented as well as today's high power diode laser beam quality limit shown in fig.15, there are still applications with a high potential available for the high power diode lasers. On the contrary, a further comparison of fig.15 and fig.16 under the point of view of the diode pumped solid state lasers shows, that these lasers will extend the field of possible applications of solid state lasers into "classical" CO_2 applications, especially in the field of 3D-cutting, because of their superior beam guiding possibilities in fibers.

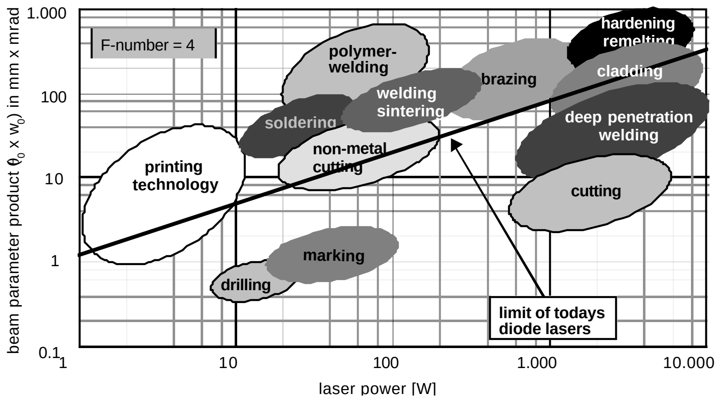

Fig16: Parameter field for laser materials processing (after [15])

3.1 Diode Lasers

Some of the applications above the diode laser limit line have been demonstrated years ago with Nd:YAG or CO_2 lasers, but could not penetrate into the industrial manufacturing for technological or - mainly - cost reasons. The investment costs of today's high power diode laser systems are in the range or even below those of CO_2 lasers and, thus, already considerably less than Nd:YAG lasers; the running costs are much less than those of conventional lasers because of their high efficiency (typically the wall plug effiency is in the range or even above 30%) and since they are almost service free over the lifetime of the diodes. Considerable reduction of the running costs is expected with the increase of lifetime of the diode laser bars, since simple cost calculations show, that besides the depreciation, the replacement of the diodes creates the lion's share of the running costs[2)]. Last but not least, the small size of not only the diode laser head, but - based on the high electrical to optical efficiency - also of the power supply and the chiller, make them a very attractive tool for many of these applications, where beam quality of the conventional laser is simply not necessary.

Besides polymer welding, which has been applied for the first time in manufacturing of an electronic key [17, 18], heat conduction welding and surface treatment are successful applications of diode lasers in a manufacturing environment today; a short description of other applications can be found in the literature [19].

3.1.1 Esthetic Weld with Diode Lasers for Manufacturing of Kitchen Sink [20]

[1)] If BPP is different in x- and y-direction, geometric average ($\langle BPP \rangle = \sqrt{BPP_x * BPP_x}$) is taken in the graph

[2)] This is not only true for the high power diode lasers, but also for the diode pumped solid state lasers

The possibility to produce optically perfect seams lead to the very first industrial application of high power diode lasers, the welding of kitchen sinks (fig.17). The use of the diode laser instead of conventional TIG welding allowed a considerable reduction of after-work: only polishing is necessary, but no grinding or repair! This fact led to a cost benefit, even if of course the investment for a 2,5 kW diode laser is higher than for a TIG welding machine. The laser is mounted onto a robot arm, which guides the laser over the weld seam with a speed of about 1 m/min; this is also a unique feature of the diode laser, which makes complex beam guiding equipment unnecessary. The application is run in manufacturing since more than two years now successfully.

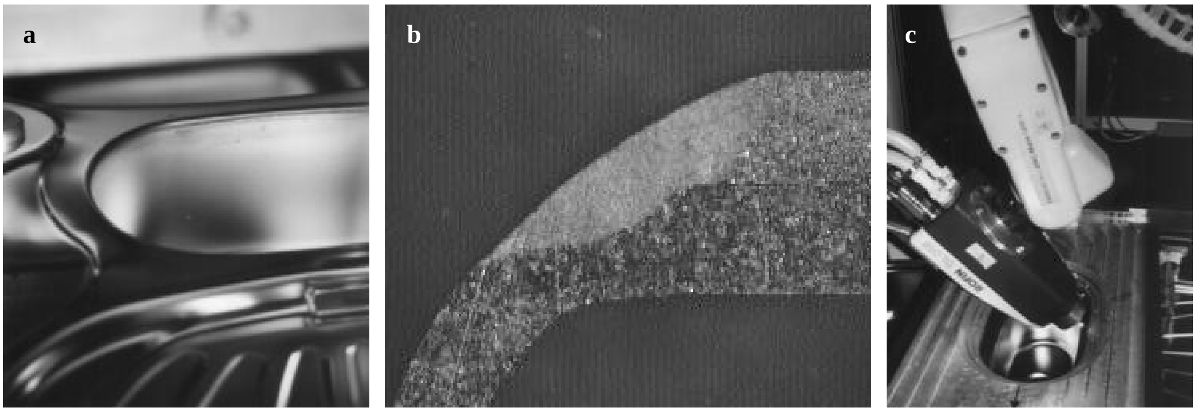

Fig.17: Welding of kitchen sink with high power diode laser [20]. a: kitchen sink after welding (before polishing); b: cross section of a weld seam; c: positioning of laser head with the robot;

3.1.2 Harding of Torsion Springs for Car Door Hinges [21]

Another example of a manufacturing application of high power diode lasers is the hardening of torsion springs, which are used at the angles of car doors (fig 19a). At those places, where the clamping rolls click into place to keep the door in certain positions wear at the surface of the spring takes place. To increase the life time of the spring, the torsion springs, shown in fig. 19b have to be hardened over an angle of >170°, over a length of ca. 10 mm and to a depth of 0.2 to 0.4 mm at the position, which is marked by an arrow. The high power diode laser does not only provide an ideal beam geometry and intensity distribution, but is also the most cost efficient tool for the transformation hardening. With a set-up, which uses two lasers under an angle of about 120° and a water cooled fixture for the torsion spring (fig 19c), this geometry can be hardened homogeneously (see fig. 19d), if the lasers scan over the 10 mm length. An active process control, which uses two pyrometers for temperature recording assures the quality for each individual part. The cycle time in the manufacturing line is 2 seconds; the laser is on for 0,8 s and off for 1,2 s; manufacturing takes place 24 hours a day, 6 days a week. Two manufacturing systems with two 1,5 kW lasers each are in production since 16 months now and more than 12 million springs have been manufactured so far without any major problem.

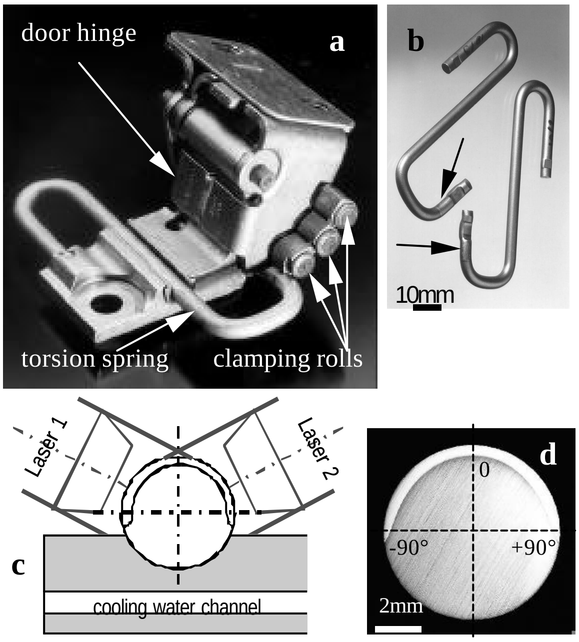

Fig. 19. Hardening of torsion springs: a: door hinge, b: torsion springs, c: hardening setup with two lasers and watercooled fixture; d: cross section

3.2 Diode Pumped Solid State Lasers

Whereas the diode laser applications often differ from the "traditional" use of lasers because of their special features, the diode pumped YAG lasers are applied mainly in the well known laser applications of cutting and welding. Of course, beyond the advantage of the elimination of arc lamps for pumping the diode pumped solid state laser offers new possibilities because of its superior beam quality. This results in either higher power density and thus, higher process efficiency at constant working distance or in a higher working distance at constant power density (if compared with lamp pumped unit of the same power).

3.2.1 Cutting application

Because of the high beam quality of the diode pumped NdYAG lasers they gain more and more interest for cutting applications, especially if three dimensional parts have to be treated. In fig. 20 characteristic cutting data for mild steel and a 600 W resp. 1200 W laser with a 300 µm diameter step index fibre are presented. A prominent application of these lasers is the cutting of three dimensional hydroformed parts as shown in fig. 21.

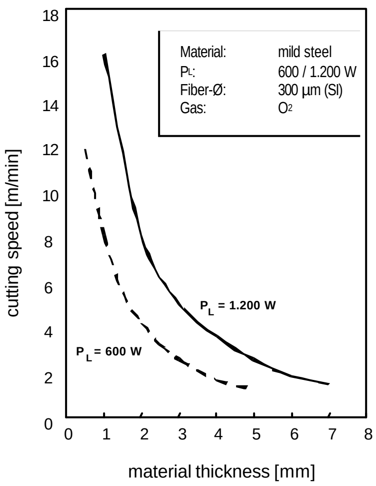

Fig. 20 (left): Cutting curves for diode pumped NdYAG laser

Fig. 21 (top): cutting of hydro-formed parts with a diode pumped Nd:YAG laser

3.2.2 Welding application

The improved beam quality of the diode pumped NdYAG laser (12 mm mrad) as compared with lamp pumped systems (25 mm mrad) leads - as expected - to an increase of the welding speed for the same welding depth, if same focal length and same power on the work piece are used, as shown in fig 22. The high flexibility using a fibre as the beam delivery system makes the laser to a welding system, with almost no competition for complex geometries, especially for those, which are only accessible from one side. An example is the stitch welding process performed on car doors at Porsche and which is shown in fig. 23. This process leads to an increased strength of the part [22].

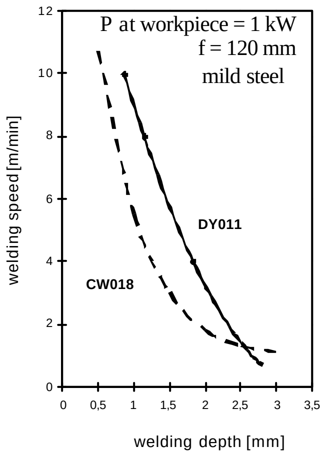

Fig.22 (top): Comparison of welding speed for lamp (- - -) and diode (—) pumped laser

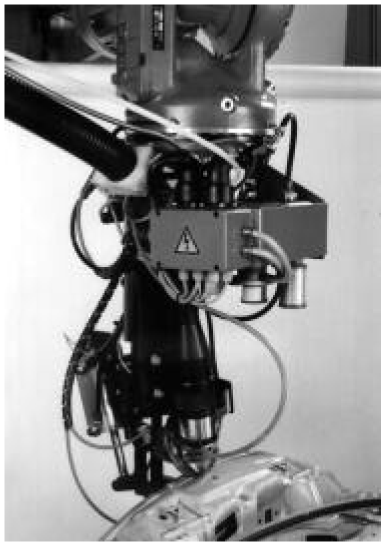

Fig. 23 (right): Welding head for car door welding with diode pumped Nd:YAG laser (Source: Porsche AG, Kuka GmbH)

4. Future Outlook – National Programs

The production numbers resp. the turnover of laser sources for materials processing (CO_2 and NdYAG) has been increased form 165,2 Mio. DM in 1994 up to 523,3 Mio DM in 1999, according to a recent investigation of the VDMA (**V**erband **D**eutscher **M**aschinen- und **A**nlagenbau[3]) [23]. At the same time, the export of laser sources has increased from 65.5 Mio. DM to 189,2 Mio. DM, remaining more or less constant at 35 to 40% over this time. Thus, the world market for materials processing [6, 7] is covered to about 1/3 by German lasers. This strong position of Germany in the laser market is among others a consequence of a unique infrastructure of laser oriented institutes all over the country and of thorough research programs, which are funded from the Bundesministerium für Bildung und Forschung BMBF[4] and which are mainly administered from the VDI-TZ (Verband Deutscher Ingenieure – Technologie Zentrum[5]). To elaborate the scientific and technical fundamentals, to reduce the barriers for existing or new laser applications and to assure a continuous competitive position of Germany in laser technology in the 21^{st} century the "Laser 2000" concept was launched 1993 by the BMBF and the German laser industry. The main targets of "Laser 2000" are:

- fundamentals for new laser generations,
- fundamentals to open up new applications,
- precision processing with lasers and
- laser medicine.

The projects described below in more detailed are organised under the roof of this successful Laser 2000 structure.

---

3) German Association of Machine Tool and Systems Manufacturers
4) Federal Ministry of Education and Research
5) Association of German Engeneers – Technology Center

NOVAtive LASersysteme auf der Basis von Hochleistungsdiodenlasern[6)] [25]

This program is the succeeding activity to the program "High-Power Diode Lasers and Diode-Pumped Solid-State Lasers", which has been run between 1994 and 1997. In five subnetworks 52 projects are elaborated (see fig. 24) from 29 institutions out of which 20 are institutes or universities and 9 are industrial partners. The project is directed by the Fraunhofer Institute for Applied Solid-State Phsics[7)]. The project period is scheduled from 1998 to 2002; the total budget is 96 Mio. DM, with a funding of 48,4%.

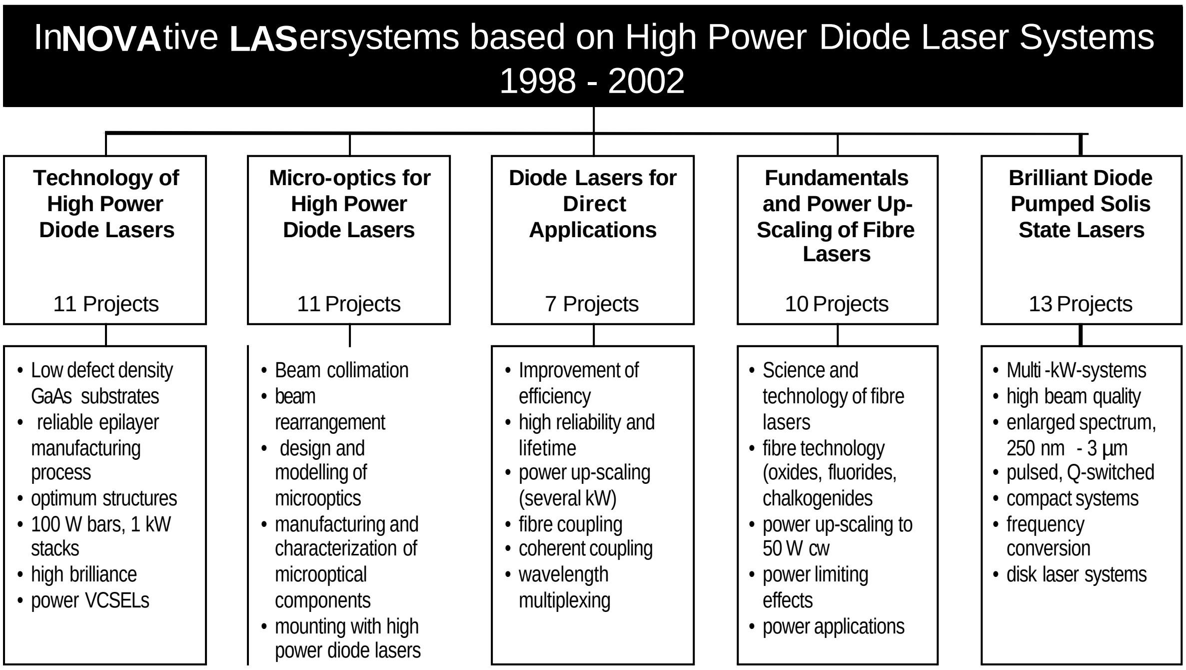

Fig. 24: Structure, Projects and Targets for the NOVALAS Project

Modulare Diodenlaser Strahlwerkzeuge[8)]

It is expected, that diode lasers will be a revolution in manufacturing technology and will enhance the number of laser processes in industrial manufacturing lines considerably world wide. The MDS-project, with 22 partners from industry and 6 from institutes - is aimed to the diode laser and laser systems technology and generates the fundamental knowledge for the application of these laser systems. The partners are vertically organized in three groups

- chip technology
- laser and systems technology and
- applications and production technology.

At the beginning of the technology chain, new semiconductor chips will be developed and manufactured to provide an output power and a beam quality, which are above state of the art technology by a factor of 2 to 5. These new chips will be assembled by the partners of the laser technology group to high power laser systems. For this task techniques for micro-optic beam forming and beam combination have to be developed, which are about ten times as powerful as those which are in use today. It is the task of the partners at the end of the chain, i.e. the application technology, to further develop the present knowledge about the laser as a tool, so that the specific advantages of the novel diode laser beam tools will be applied in manufacturing processes with considerably increased quality and with high economic efficiency.

The project has a budget of about 78 Mio. DM, which is funded from the German Ministry of Education and Research (BMBF) by 46.7 %. The budget is spent to about 50% for the investigation of applications resp. the adaptation of applications to the special features and benefits of the high power diode lasers; the other half is split to about 50% each for the semiconductor development and the laser and systems integration technology. The duration of the project, which has been started at July 1st, 1998 will be 5 years.

4.2.1 The technological plan

---

6) Innovative laser systems based on high power diode lasers

7) Coordinator of the p rogram is Dr.Roland Diehl, Fraunhofer Institute for Applied Solid-State Physics, Tullastr. 72, D-79108 Freiburg / Germany, e-mail: diehl@iaf.fhg.de

8) Modular Diode Laser Beam Tools

The project is vertically structured in that sense, that each group is dependent from the success of the one above: The "Chip Technology" group delivers the bars for the integration into systems, which is to be performed in the "Laser- and Systems" group; these systems are matched with the requirements of the applicants in the "Application and Production Technology" group.

4.2.1.1 Chip Technology

Naturally, at the beginning of the technology chain the semiconductor technology is located. Diode laser bars with output power and beam quality, which are both a factor of 2 to 5 above today's values are required for the future systems. At the same time, of course, degradation behavior, i.e. life time has to be improved and costs have to be maintained or even reduced further. The semiconductor development is performed in three steps with increased technological difficulty. The optimal values of focal intensities are directly linked to the beam quality of the laser bar. Each new generation of bars, which is represented by "band 1" to "band 3" in fig. 25 leads to an improved system generation for a special application. In band 1 and 2 conventional "wide area emitter" diode laser bars will be further optimized in terms of output power, beam quality, available wavelengths (for λ-coupling), lifetime etc., and especially be matched to the requirements of optimized micro-optical devices, which are essential for efficient coupling. In band 3 new types of emitters with a considerable improvement in beam quality, e.g. tapered laser arrays, shall be available for the integration into high power diode laser systems.

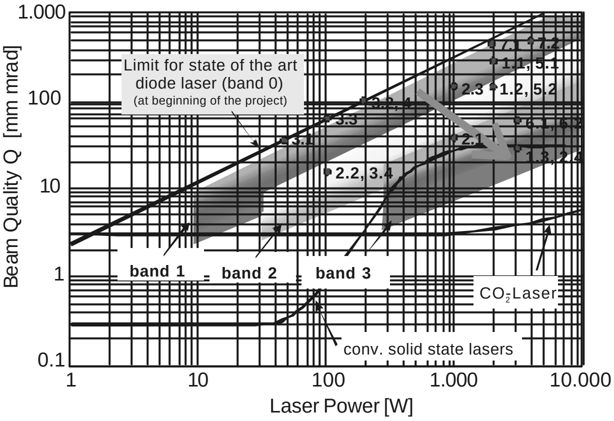

Fig. 25: Development of chip technology is performed in three steps, which leadstothree "bands", where systems can be realized ("band 0" represents the situation at the beginning of the project).

4.2.1.2 Laser- and Systems Technology

The partners in the laser- and systems group will further process the diode laser bars, developed and manufactured from the chip technology group; the bars will be mounted onto micro channel heat sinks, coupled with micro-optical components and assembled to high power diode laser systems, which are suitable for materials processing applications,. New mounting technologies, novel beam forming and combining techniques must meet the 10-fold increase of performance of the laser bars. Flexibility must, nevertheless, be maintained or even increased at the same time: one of the essential differences of high power diode lasers and conventional lasers is the modular structure, which allows totally new approaches to the laser materials processing. It is another, very important goal of the project to set the fundamental technologies or concepts for modular, but standardised base modules, which can provide the basis for beam sources, which are ideally adapted to the requirements of the process. Comparison of the beam quality with the conventional NdYAG and CO_2 lasers, as shown in fig. 25 and also fig. 15 clearly demonstrates, that in the near future high power diode lasers may touch the field and applications of lamp pumped (cw-)NdYAG lasers, but will neither come into the diode-pumped NdYAG area, especially not the disk laser area, nor into the CO_2 laser area and applications, which require high beam quality.

4.2.1.3 Applications and Process Technology

In frame of the work of the chip technology group and the laser and systems group, which have been described above, laser systems are generated, which are tailored according to the requirements of the planned applications. The applications are divided in seven work packages:

1. Joining of sheet metals: sheet metals, car- and airplane structures
2. Novel cutting technology: coil materials and metal foils
3. Micro-joining in electrical technique and electronics: soldering of IC's on PCB's, micro welding
4. Polymer joining technology
5. Repair and Generation: on-site use for large components, large motor axles, turbines
6. Integration of diode lasers in machine tools
7. Hardening: deep drawing and injection molding tools, automotive components

Systems have been defined in the definition phase of the project regarding power, beam quality and shape. The systems specification (without the special beam shape) can be found in fig. 25, represented by the dots: 1.1, 1.2, 1.3 represent systems used for working package 1, joining of sheet metals; 2.1 through 2.4 systems used in working package 2, cutting , and so on.

4.3 LEICHTER – Innovativer LEICHTbau durch enERgiereduziertes Fügen mit Lasersystemen neuester Generation[9)]

Not only for car industry, but also for other transportation systems, as ships, trains and airplanes, saving of resources, i.e. reduction of fuel consumption is a mandatory challenge for the 21st century. Two approaches are most promising to reach this goal: improvement of the engine efficiency and reduction of weight. Highest potential of weight reduction in a car is the car body, but also the chassis and the engine with the gear unit. At the moment aluminum is the most important material for light weight body structures. Today's standard joining technologies, TIG and MIG welding are on their limits for these materials and structures. The laser offers joining without surface preparation and with very reduced thermal distortion at high speed; another advantage of the laser welding is, that accessibility is only necessary from one side, which allows joining of especially structured units, e.g. profiles or tubes, which in turn offers another potential for weight reduction. Even if widely used, lamp pumped NdYAG lasers require high investment and running cost with a rather limited beam quality, which leads to low process efficiency, low tolerance and limited applicability for complex structures. Diode pumped NdYAG lasers show the potential to overcome most of these limitations (see 2.3). This project will work out the potential and limitations of diode pumped NdYAG lasers for the joining technology of light weight structures in five subprojects:

- light weight structures
- processes
- systems technology
- simulation
- application tests

The project is lead by AUDI AG; it has been started in March 1999 and will last until Dec 2001; the total budget is 31 Mio. DM and the funding is in the range of 50%.

5. Conclusion

High power diode lasers are not only a reliable replacement for arc lamps as a pump source of conventional rod-type solid-state lasers – as originally planned. They also make new solid state laser concepts possible, e.g. the disk laser or the fibre laser; these concepts lead to a considerable improvement of reliability and beam quality of solid-state lasers. Furthermore, and probably most interestingly, diode lasers could be scaled up to high power kilowatt laser sources, which have entered industrial materials processing recently. The incoherent coupling of the single emitters, which is used to reach high power, leads to a moderate beam quality, but their high efficiency provides a high potential for those applications, where moderate beam quality is sufficient or even necessary. A totally new approach to use lasers for manufacturing is the possibility to generate a modular concept, which is especially adapted to the needs of the application of these lasers. Ambitious research programs are performed in Germany, which underline the importance of the new laser technologies as an enabling technology in the 21st century.

7. References

[1] R.N.Hall, G.E.Fenner, J.D.Kingsley, T.J.Soltys, R.O.Carlson, *Phys. Rev. Lett.* 9, 366 (1962)
[2] M.I.Nathan, W.P.Dumke, G.Burns, F.H.Dill jr., G.Lasher, *Appl. Phys. Lett.* 1, 63 (1962)
[3] T.M.Quist, R.H.Rediker, R.J.Keyes, W.E.Krag, B.Lax, A.L.Whorter, H.J.Ziegler, *Appl. Phys. Lett.* 1, 91 (1962)
[4] I.Hayashi, M.B.Panish, P.W.Foy, S.Sumski, *Appl.Phys.Lett.* 17, 109 (1970)
[5] Zh.I.Alferov, V.M.Andreev, D.Z.Garbuzov, Yu.V.Zhilyaev, E.P.Morozov, E.I.Portnoi, V.G.Trofim, *Fiz. Tekh. Poluprovodn*, 4, 1826 (1970) resp. *Sov. Phys. Semicond.* 4, 1573 (1971)
[6] R.V.Steele, *Optoelectronics Report*, 7, 3, Feb 1st, 2000
[7] U.Brinkmann, *Optotoelectronics Report* June 15, 2000, p.4
[8] Patent No. DE 195 00 513 C1; Dilas Diodenlaser GmbH, Mainz, Germany
[9] F.Bachmann, *Proc. SPIE* Vol. 3888, p.394 (1999)
[10] B.R.Marx, *Laser Focus World*, May 1998, p.32
[11] Patent No. DE 44 38 368 C2; Fraunhofer-Institut für Lasertechnik, Aachen, Germany
[12] C.Emmelmann, *Laser Opto* 1/99, p.47, (1999)
[13] see www.rofin.com
[14] A.Giesen et.al. *Appl. Phys.*, B58, p. 365 (1994)
[15] P.Loosen, Fraunhofer-Institut für Lasertechnik, Aachen, Germany, pers. communication
[16] D.Petring, LaserOpto 31, (5), 6 (1999)
[17] D.Hänsch, G.Treusch, S.Pflüger, *Modern Plastics*, Sept. 1997, p. 121
[18] F.Bachmann, R.Takahashi, S.Fujishima, Proc. of LPM-2000, Omiya City, Saitama, Japan, June 14-16, 2000, to be published
[19] F.Bachmann, GCL-HPL Conference, Florence, Italy, Sept 18-22, 2000 to be published in *Proc. SPIE*, 2000
[20] C.Brettschneider, *Laser-Praxis* 2/98 p.10 (1998)
[21] B.Schürmann, F.Bachmann, *Laser-Praxis* 1/2000 pp. 14-16 (2000)
[22] T.Posch, *Produktion*, Vol. 36, Sept. 1997
[23] N.N., *Eurolaser* 2, June 2000, p. 16
[24] N.N., Laser 2000, ed. by BMBF (1995), ISBN: 3-88 135-277-5
[25] for details see http://novalas.fhg.de

[9]) Innovative light weight assembly by energy reduced joining technology with laser systems of newest generation