High Power Diode Lasers and Current Applications

Enabling features for DPSSL and laser micro processing

In the recent years diode lasers have been established in many areas of industry and research. Especially the pumping of solid state lasers (DPSSL) is major field of application for high power diode lasers enabling solutions in many laser micro processes like cutting, sintering, structuring as well as drilling. This article reports progresses in the past as well as state of the art of high power diode lasers and describes their major applications.

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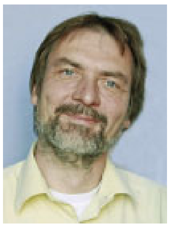

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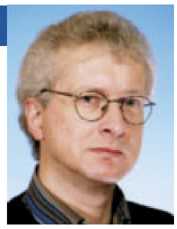

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High power diode lasers (HDL) became a regular tool in manufacturing about 10 years ago. At that time the most advanced diode laser manufacturers were able to demonstrate lifetimes above 10,000 hours. The power level from that time was a standard for a long period: 40 W cw conduction („passively") cooled and 50 W micro channel („actively") cooled. As seen in Fig. 1 this cw power level remained the standard for the last 15 years (Fig. 1).

Before, the major market for cw HDL was primarily research orientated. The lifetime was a matter of academic interest. While hovering at the 50 W level, lifetime developed from 2,000 hours to 10,000 hours. Due to the fact that the price of diode laser light source scales much more with the number of diode lasers than with power to drive towards higher power per bar fuelled a race to the highest power per bar once the 10,000 hours lifetime target was met. To secure and extend the lifetime capabilities numerous diode lasers and burn-in racks were dedicated to data generation.

Two ways of improving HDL made this development possible: The improvement of the electro-optical efficiency of the semiconductor and the improvement of the capability of heat sinks to remove heat from the semiconductor. Both processes enhanced each other and both gradual and stepwise developments to better products can be found through the history of HDL of the last 10 years.

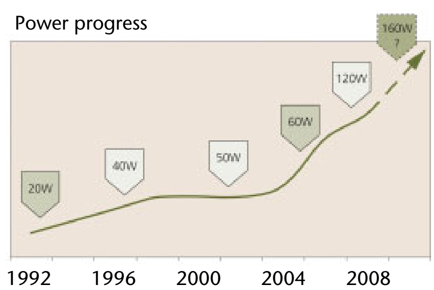

FIGURE 1:
Development of cw optical output power from one bar over time.

Efficiency

High power diode lasers are the most efficient artificial light sources. Still, a significant part of the electrical energy is converted to heat in a diode laser (Fig. 2a). Several years ago the SHEDS program in the USA triggered a move towards higher efficiency worldwide. Jenoptik developed the diode laser structures at about the same time with the identical target: get more efficient diode laser material. The result can be seen in Fig. 2b. A moderate raise of the wall plug efficiency (WPE) from 50 % to 60 % allows for 50 % more optical output power under identical heat removal conditions. Today, for 808 nm material WPEs around 60 % are common. For 9xx nm material the value are even better: There the numbers are around 65 % WPE. These values carry already the ohmic losses of the diode laser package, which are in the range of 7 % to 8 %. This means that the electro-optical conversion efficiency in the semiconductor may be above 72 % in the case of 9xx nm material.

The improvement of the efficiency of the semiconductor material in many cases leads to disadvantages of other properties as waveguide and quantum well modifications influence both properties. Especially the fast axis divergence is one of these influenced properties. A lower divergence is important if the diode laser light is to be delivered by a fiber and therefore divergences govern the fiber-coupling efficiency. Fig. 3 illustrates the decrease of WPE with improving fast axis divergence. This may demonstrate that record efficiencies are important to understand the internal diode laser structure and to develop is further. But for practical applications other properties of the diode laser material factor in, too.

Lifetime

The general assumption is that diode lasers are very delicate parts with short lifetimes. If basic procedures are obeyed as protection from humidity, dust, and electrostatic discharge the lifetime of diode laser is several ten thousands of hours. The ISO 17526 governs the lifetime definition, which is not used in the telecom arena. Therefore, it applies to all high power diode lasers.

The general failure process is degradation of the semiconductor material, which shows as decreasing of optical output power at constant current. This process can be measured and enables an extrapolation if more than 20 % of the initial power is lost due to degradation. The mark of 80 % start-of-life power usually is considered as the end of life criterion.

As the degradation process is a thermally activated process, it depends on the junction temperature of the diode laser bar. In consequence, as with all other types of lasers the cooling is the key to both power and lifetime. For diode lasers two basic cooling concepts have been developed. There is the active cooling with water which runs right through the copper the diode laser bar is mounted on. This cooling is very efficient in terms of heat removal since the generated

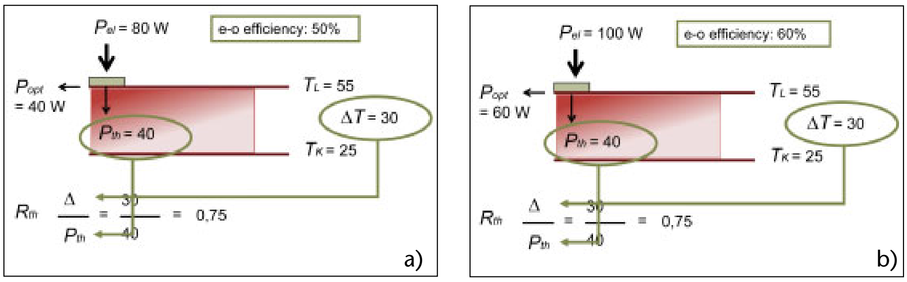

FIGURE 2:
Improvement of the diode laser wall plug efficiency (WPE) from 50 % to 60 % allows raising the power from 40 W to 60 W, respectively.

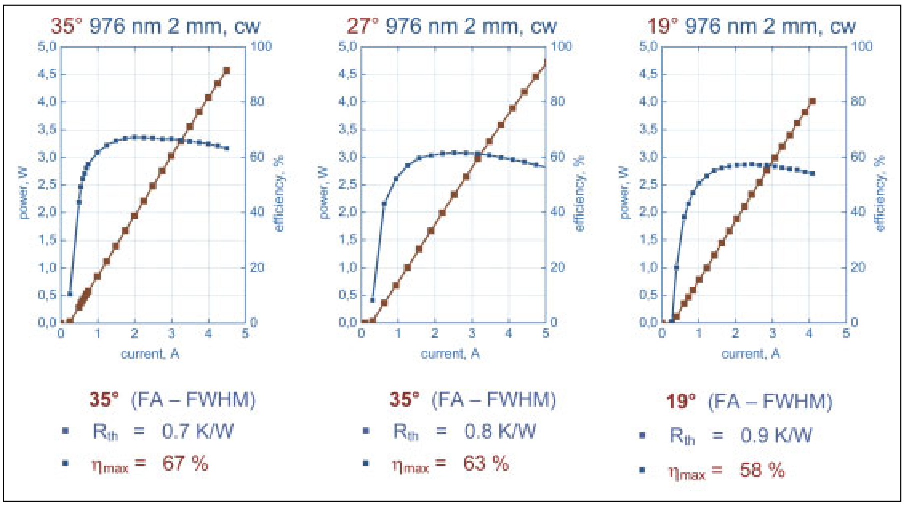

FIGURE 3:
Reduction of wall plug efficiency with improvement of fast axis divergence.

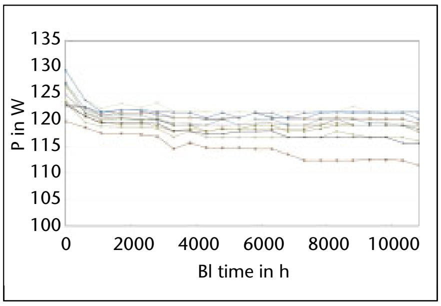

FIGURE 4:
Typical degradation curve: For a 120 W device the 80 % power line is at 96 W. Even after more than 10,000 hours the power loss is typically less than 5 %.

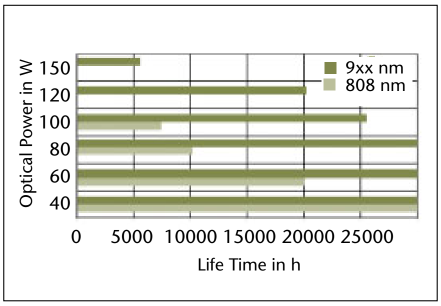

FIGURE 5:
Expected life time at different optical output power levels for 808 nm and 9xx nm.

heat is moved away without much spreading. However, the water has to run through one electrical contact. Therefore it has be deionized to suppress any remaining electrical conductivity. This enables chemical erosion processes and forces a careful choice of material for those parts, which have contact to deionized water. Some users acquired the ability to run these heat sinks consistently over 20,000 hours and more. Still this cooling concept is considered to be complicated and the other cooling concept passive cooling where the heat is removed by heat conduction only becomes more and more important to get to lifetimes of 20,000 hours and beyond.

This leaves us with the issue of the degradation of the semiconductor bar material. A typical degradation curve is shown is Fig. 4. After a typical burn-in drop of power which happens before delivery the power is quite stable over time. After more than 10,000 hours the power is typically less than 5 W of 120 W. One laser of the set did not meet the spec from the beginning. But all other lasers show a degradation behaviour which let

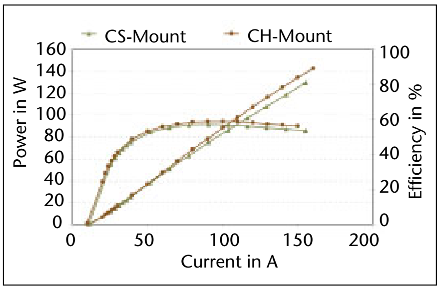

FIGURE 6:
Comparison of electro-optical data of passively cooled diode lasers between the industry standard of passively cooled diode lasers (CS) and Jenoptik design (CH).

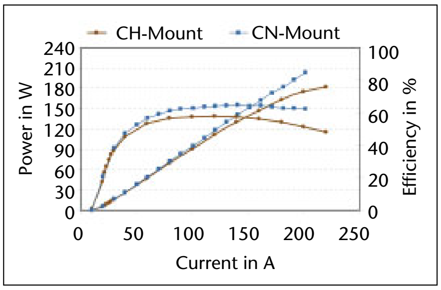

FIGURE 7:
Comparison of the electro-optical data of passively cooled diode lasers between the current standard Jenoptik design (CH) and the new Jenoptik design (CN).

FIGURE 8:
The fiber-coupled module JOLD-100-CPXF-2P A based on CN type of diode lasers delivers 100 W from a 0.4 mm fiber with a total wall plug efficiency of 42 %.

them reach the 80 % start of life power level at 96 W long after 20,000 hours operation.

This type of data has been generated over time for all types of diode lasers. And it is still being generated for the more recently introduced types. From this data expected lifetimes were derived, the times of operation where less than 5 % of the lasers should lose more than 20 % of their power at start of life. The result is shown in Fig. 5. The 9xx nm material (88x nm, 915 nm, 940 nm, 980 nm) in general turns out to be more stable than the 808 nm material.

New concepts

Knowing that semiconductor efficiency and mounting quality are key fields of further improvement most of the work is done in these areas to further improve high power diode lasers.

When comparing the industry standard design of passively cooled diode lasers (CS) with our design (CH) we found that an extension of the heat sink in forward direction improves heat spreading, therefore reduces the junction temperature at 120 W operation by about 8 K which doubles the expected lifetime because the degradation rate is reduced to 50 %. Fig. 6. shows a comparison of the electro-optical data of both types.

The improved head spreading of the CH design can be combined with an additional heat removal from the n-contact side of the diode laser. Fig. 7 shows the further improvement with this new CN design. The wall plug efficiency reaches 63 % at about 160 W optical output power. With this advanced heat sink design the roadmap of Fig. 1 becomes reality.

Instead of ramping up the power because of the better heat removal the alternative is to operate the diode laser at elevated cooling temperatures. This has been done with a fiber-coupled module, which delivers a power of 100 W at 915 nm from a 0.4 mm fiber. This module was cooled with forced air instead with water (Fig. 8). The wall plug efficiency decreases compared to water cooling but the advanced cooling of the semiconductor keeps the junction temperature low enough to expect lifetimes of at least 20,000 hours. The total wall plug efficiency of the fiber-coupled module in the forced air cooled regime is above 42 %.

Application of novel diode laser designs in new solid state lasers

The major application of high power diode lasers is pumping of DPSSL (Diode-Pumped Solid State Lasers). In every solid-sate laser so-called thermal lensing occurs which is generated by the temperature enhancement inside the laser medium along the beam axis of the solid-state laser. In the result beam quality and the possibility to focus down laser light will be reduced by this effect. The driver of this process is energy loss of the pumping process. Because spectral emission profile of diode lasers can be matched to the absorption profile of the solid-state laser materials, the energy loss in the pumping process is minimized. Thus diode lasers are an excellent tool for pumping.

One type of DPSSL with minimized thermal lensing in particular is the thin disk laser. There has been a successful product line of thin disk laser from Jenoptik for many years. Now, the recent progress in diode laser technology in combination with the well established thin disk laser technology lead to the launch of a completely new Jenoptik solid state laser.

The model "JenLas® *disk IR50*" overcomes common restrictions to run a pulsed laser: Normally pulse repetition rate, pulse energy and pulse duration are bonded together.

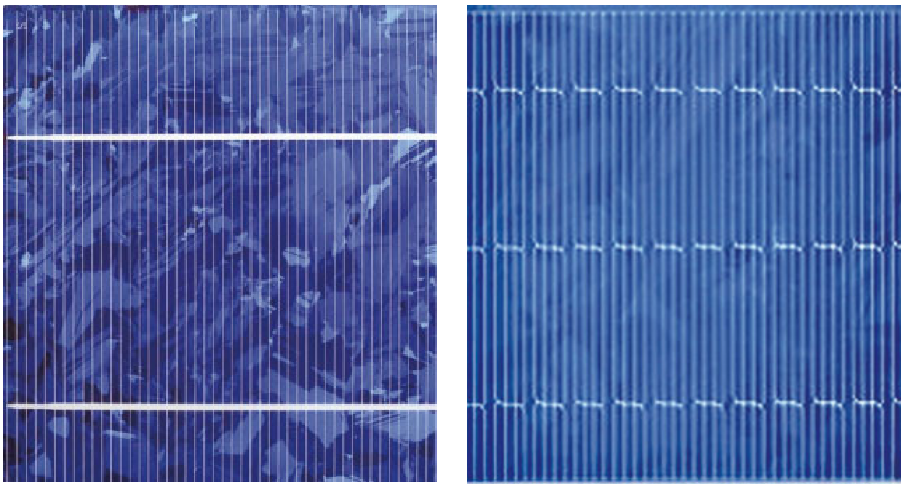

FIGURE 9:
Comparison of standard (left) and new cell concept (right) for Silicon-based solar cells: "wrap-through" concepts put the front contact bars to the backside. The photoelectric "dead zone" below the contact stripes is reduced and total cell efficiency will be enhanced. For this a fast laser drilling process is required.

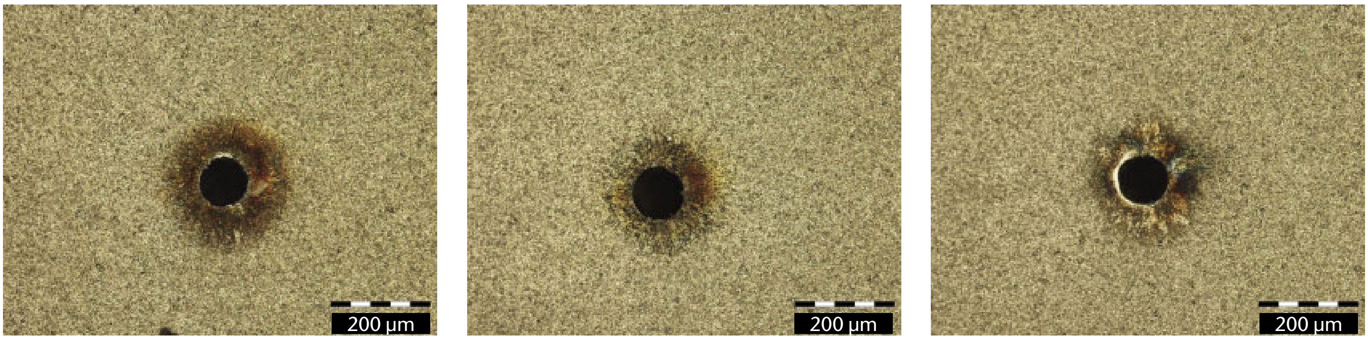

FIGURE 10:
Laser drilled holes of 80 µm diameter into 0.2 mm Silicon wafers. Edge of hole shows significant change in quality depending on laser pulse duration (from left: 300 ns, 600 ns, 800 ns), best result is reached at 600 ns. Dark colouring is caused by debris, which can be removed easily in a subsequent etching step.

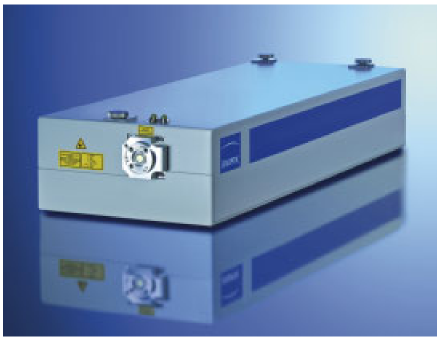

FIGURE 11:
JenLas® *disk IR50* is a q-switched 50 W-disc laser which pulse length can be tuned continuously.

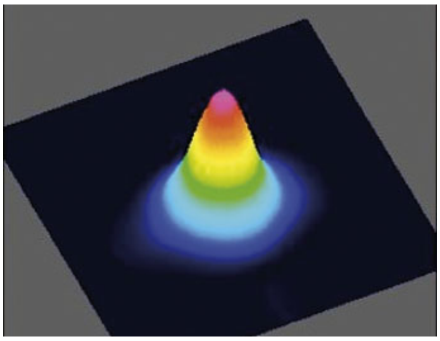

FIGURE 12:
Beam profile measurement of excellent M²=1.2 beam quality, required for good focusing.

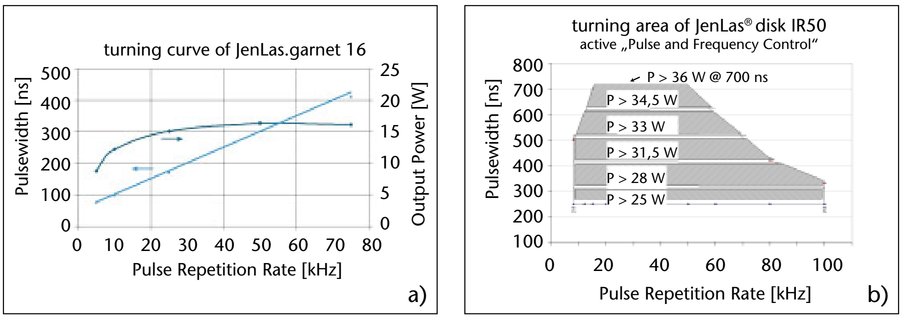

FIGURE 13:
a) Tuning curve of a conventional q-switched laser: Pulse width and output power are correlated to the pulse repetition rate.

b) Tuning area of the unique laser source: Application parameters can be optimised independently within a large parameter field. There is also a bonded tuning curve covering the range of 800-2100 ns at 8-30 kHz.

This means, one of these parameters cannot be set without influencing the others. At a power level of 45 Watt, excellent beam quality (TEM_{00}, $M^2<1.2$) features at infrared emitted wavelength of 1030 nm. The combination of high repetition rate up to 100 kHz and pulse energy up to 5 mJ delivers real laser power for fast processing speeds. Its unique ability for independent pulse length adjustment (250-2100 ns), variable pulse repetition rate (8-100 kHz) and output power separate this laser from the competition. The advantage of decoupling the pulse length and pulse repetition rate is the optimization of the laser parameters to a given application. A new method to control the pulse duration inside the laser resonator allows the laser to run beyond the limits of the classical q-switching mode.

The integrated AOM design guarantees consistent high accuracy pulse lengths without the need for first pulse suppression. The real value of the JenLas® *disk IR50* is that it produces a wide range of characteristics that would normally require multiple laser sources to be applied.

Improved drilling of PV-wafers with JENOPTIK-VOTAN™ Solas 1800

Typical applications for a laser source mentioned above are micro-cutting, micro-sintering, micro-structuring and micro-drilling. To establish this technology in demanding innovative markets like photovoltaic industry Jenoptik together with industrial project partners has investigated Silicon drilling in its own applications lab. Target application of Silicon drilling is a new solar cell concept. For this concept front-side contact bars are "wrapped-through" to the backside by drilling through-holes. Finally an electrical contact from the front-side to the back-side through the hole is generated by filling the hole with a conductive material. Advantage of this cell structure is reduced area loss at solar cells front side due to contacts and reduced electrical losses, because contacts can be formed at the backside covering a larger area (see pictures). It is important to optimize the drilling process with respect to processing speed, edge steepness and quality and of course heat affected zone.

From laser ablation of metals it is known, that there is enhanced ablation rate if pulse length in the range of some 100 ns is applied. Usual procedure up to now is just to use one laser source after the other – to evaluate ablation behaviour along the laser tuning curve of each laser. With the new laser source it is now possible to investigate the whole range systematically. Some results for Silicon drilling are shown in the photographs. The Silicon wafers are 200 µm thick, the target diameter of the holes is 80 µm and the production process requires to drill 100 holes within an area of 156 x 156 mm² in 1 sec.

As one can see, there is a significant change in the ablation result, depending on the pulse duration. An optimised operation point for the drilling process can be found at 600 ns pulse length.

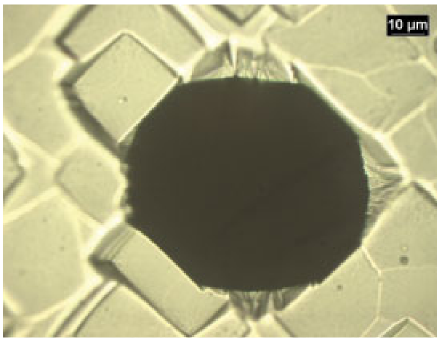

FIGURE 14:
MWT-hole under the microscope, drilled within 1.5 ms (taken after a short etching step).

Summarizing the application, one can see that there is a special knowledge required for handling heat management both in the pumping diode laser source as also in the solid state laser. Beam forming knowledge for the diode pumping beam and good understanding of resonator design and control of pulse build-up in the solid state laser form core competence of Jenoptik required to setup a novel laser source, which delivers unique opportunities of scanning its parameter area for systematic optimisation of point of operation due to the laser application needs.

JENOPTIK-VOTAN™ Solas 1800 on the way to grid parity

One of the most important economic key figures within the PV industry is the "grid parity", a comparison price of electrical energy, generated conventionally or by solar cells. The "grid parity" for PV energy can be reached by improving the conversation efficiency as well as by a reduction of the production costs.

The new IR50-based laser system JENOPTIK-VOTAN™ Solas 1800 helps to improve both factors. The electrical efficiency becomes higher by enabling the Metal Wrap Through (MWT) or Emitter Wrap Through (EWT) concept. To increase the active area of the solar cell for both concepts the conducting (metal) structures are shifted partially (MWT) or completely (EWT) from front to back-side. So the active area can be increased.

Due to the IR50 system has the above described wide range of parameters, all the different types of hole can be drilled with a high quality (see Fig. 14) within very short cycle times. Especially the variable and wide range of pulse length of the used laser gives the possibility to adept the drilling process exactly to the wafers properties like thickness or surface reflection. It was shown, that the number of pulses for one hole can be reduced down to 50 % by choosing the optimal drilling mode and pulse length. This makes the system faster and establishes the required cycle time of 1 s per wafer with one laser system. A short cycle time has a significant influence on the costs per wafer and brings the user in the PV industry closer to grid parity.

The new JENOPTIK-VOTAN™ Solas 1800 system for MWT/EWT drilling system will be offered in two versions: as a stand alone system for research and batch-processing as well as a technology module for the integration in inline-production-systems.

THE COMPANY

Jenoptik's Lasers & Material Processing division

JENOPTIK Laserdiode GmbH, JENOPTIK Automatisierungstechnik GmbH and the laser technology business unit of JENOPTIK Laser, Optik, Systeme GmbH belong to Jenoptik's Lasers & Material Processing division. This division makes Jenoptik one of the leading providers of laser technology – from components through to complete system. Lasers & Material Processing division is specialized in semiconductor materials, diode lasers, solid-state lasers and in laser processing of various materials. The increased productivity from which our customers benefit is the key factor in the use of Jenoptik laser technology.

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Summary

Diode laser technology has seen much progress during the last few years. Using diode lasers at the set of parameters which are being delivered today in pumping makes novel solid state laser features possible. Tailored toward specific applications and embedded in systems suitable systems which are optimized for productivity, quality and cost reduction diode lasers are a good choice for many applications.