Advanced Concepts of using diode lasers in materials processing

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ABSTRACT

Recent improvements in the performance of high-power diode lasers and beam shaping techniques are driving developments of diode laser systems for direct industrial material processing. The paper summarizes principle concepts, physical limits and activities at the ILT in the field of diode lasers systems and their direct applications.

Keywords: diode lasers, stacking, beam shaping, direct applications

1. INTRODUCTION

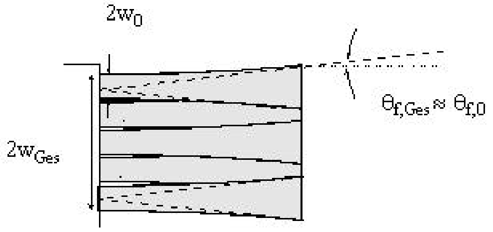
In the last few years impressive advances in the development of high-power diode lasers (HPDL´s) and their production technology have been achieved /1/. Output powers in the range up to 120 W out of one 10 mm diode laser bar have been reported /2,8/ as well as rapidly declining prices. In the past most activities concerning application of HPDL´s have been focused on the pumping of solid-state lasers, where the diodes are used as a substitute for flashlamps or arc-lamps in order to increase efficiency, beam quality, lifetime and reliability. Apart from these ”indirect” industrial applications the emission of HPDL´s may be used directly for materials processing. In most cases of direct use of HPDL, techniques for beam shaping and combination have to be applied in order to match both the highly asymmetric beam and the output power of the diode laser bars to the requirements of the application. At present the most straightforward way to do this is based on incoherent superposition of diode laser beams. The principle as well as technical set-ups will be illustrated in chapter 2 along with a discussion of the physical limits of this technology with respect to output power and beam quality. Chapter 3 gives some examples of current industrial applications of such systems.

2. PRINCIPLE OF INCOHERENT BEAM COMBINATION AND SYSTEM DESIGN

The basic principle of incoherent beam combination and its effect on beam quality is illustrated in fig. 2.1, where N beams are superimposed by putting them side by side with the maximum filling factor (”spatial multiplexing”). The output power of the total beam rises by a factor of N, the beam quality however drops: the beam parameter product (BPP_{Ges} as a measure of ”beam quality”) of the total beam is roughly N times the beam parameter product (BPP_0) of one single beam.

Fig. 2.1

Principle of ”spatial multiplexing”: incoherent superposition of N beams. (w_0 - beam waist radius , q_f - far-field divergence)

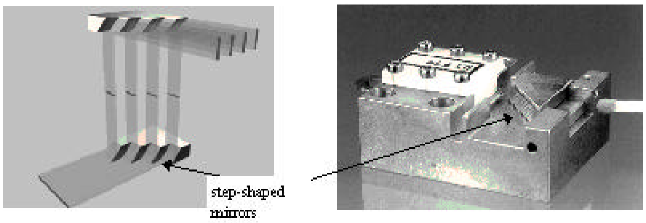


$$BPP_0 = w_0 \cdot \theta_{f,0}$$
$$BPP_{Ges} = w_{Ges} \cdot \theta_{f,Ges} \approx (N \cdot w_0) \cdot \theta_{f,0} \quad \text{(Equ. 2.1)}$$
$$BPP_{Ges} \approx N \cdot BPP_0$$

This technique may be applied to the superposition of the beams, produced by several diode laser bars (cf. fig.2.4) or of rearranged beam parts of one single diode laser bar. The beam of a typical diode laser bar is highly asymmetric with respect to size (emitting area approx. 10 mm x 2 mm) as well as beam quality (M^2_1 » 1, M^2_2 » 1.000). Fig. 2.2 shows an arrangement where the beam of the diode laser bar, which is collimated in the axis perpendicular to the p-n-junction (”fast-axis”) by a micro-cylinder lens, is split into individual beam parts and is geometrically rearranged by reflection at two step-shaped mirror surfaces. By proper choice of the geometry of this arrangement both beam quality and size of the two directions of the beam are matched and the rearranged beam can be coupled into a fibre of circular cross-section or applied directly to the workpiece.

Fig. 2.2

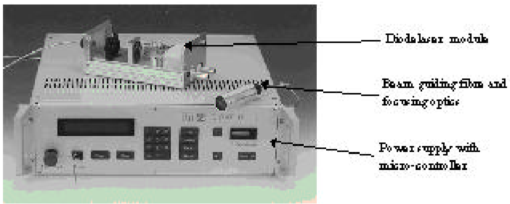
Transformation of the beam of a diode laser bar with step-shaped mirrors: principle (left) and technical set-up (right)



Entire systems for industrial applications utilising such or similar techniques /e.g. 9/ are available in the meantime /5,6,7,10/; a fibre-coupled set-up based on components as illustrated in fig. 2.2 is given in fig. 2.3, including the beam-transformation unit, fibre-coupling and microcontroller equipped power-supply.

Fig. 2.3

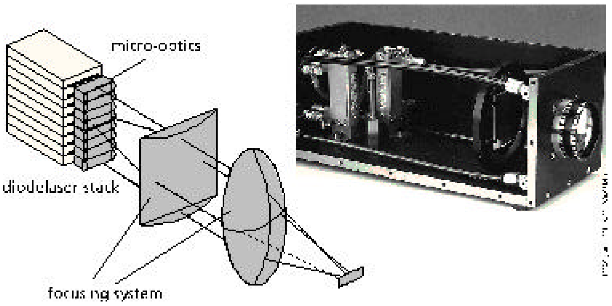
Industrial diode laser system, based on the technique shown in fig. 2.2. The system delivers output powers in the range from 20-40 W, from a fibre of 0.6 mm core diameter (@ NA 0.2). For better visualisation the diodelaser module has been taken out of the power supply.



In principle this technique can be scaled to higher output powers by bundling of several fibres, however in the kW-range a more cost-effective way to construct diode laser systems employs stacking techniques (fig. 2.4), where a couple of diode laser bars with beams individually collimated in the fast-axis are put on top of each other in order to increase output power and to match beam shapes.

Fig. 2.4:

Stacking of diode laser bars, principle set-up (left) and laboratory system (right). The laboratory system in the right-hand part of the picture has an output power up to 1.3 kW at abeam-parameter product of approx. 500 mm ·mrad, calculated according to equ. 2.2. Two stacks are combined by polarisation multiplexing (cf. Fig. 2.8)



In fig. 2.5 a comparison of diode laser systems and conventional lasers systems (CO_2- and Nd:YAG solid-state) is made with regard to rated output power and beam quality, measured as beam parameter product (BPP). Conventional CO_2- and Nd:YAG solid-state lasers are available with diffraction-limited beam quality (BPP » 0.3 mm·mrad for Nd-YAG- and » 3 mm·mrad for CO_2-lasers) at low output powers. If the rated output power rises, the beam quality drops: commercially available systems are located above the indicated curved lines in fig. 2.5.

The shape as well as quality of laser beams in materials processing are usually radially symmetric and beam quality is characterised by a single beam parameter product. In cases as described in fig. 2.2, where the diode laser beam is transformed into a symmetrical one, the comparison between diode lasers and conventional lasers can be made directly. In cases as shown exemplary in fig. 2.4, where an asymmetry remains, we eased the comparison with conventional lasers by calculating a symmetric beam parameter product according to the relation:

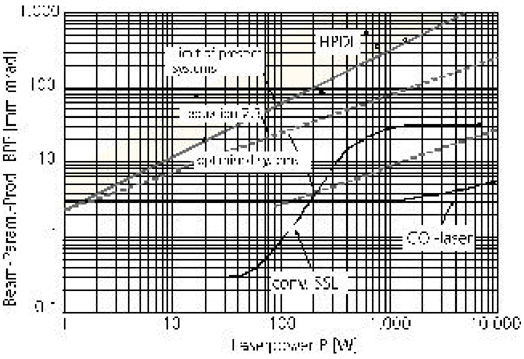
$$BPP_{symm} = \sqrt{BPP_1 \cdot BPP_2} \quad \text{(equ. 2.2)}$$

Incoherent beam superposition, as discussed previously, is characterised by the property that the total brightness of the beam (B) in the ideal case can only be conserved, in practise it will be reduced more or less by inevitable losses of power and beam quality /3/. For the ideal case it follows, that the beam parameter product or the beam propagation constant resp. (M^2=BPP/l/p) of a rotational symmetric beam goes up with the square-root of the total laser power (P):

$$B \propto \frac{P}{BPP^2} = \text{const} \qquad \rightarrow \qquad BPP \propto \sqrt{P} \quad \text{(Equ. 2.3)}$$

Fig. 2.5:

*CW laser power and beam quality, measured as beam-parameter product, for conventional CO_2- and Nd:YAG solid-state lasers in comparison to high-power diode lasers with incoherent beam superposition. The line with reference to equation 2.3 is calculated for the combination of an appropriate number of conventional multi-stripe emitters (*l=940 nm), each having 1 W power and M^2 *1.5 in the fast and* M^2 *30 in the slow direction.*



The output power and beam parameter product of presently available commercial diode laser systems are located above the solid straight line in fig. 2.5 and thus some factors away from the theoretical limit, given by equation 2.3. Reasons for this are manifold:

- The biggest cause for losses are the microoptical elements for fast-axis collimation /4/: power throughput of these elements is typically in the range of 70%-90%, depending on the quality of the lens and the NA of the beam; losses in beam quality may amount to a factor of 2-3 in good cases, for bad quality lenses and beams of high NA degradation by a factor of up to 10 or more is not unusual.
- Even a high-quality lens may cause beam degradation due to positional tolerances caused by low mounting accuracy and low thermal stability; an accuracy in the mm-range is needed for both the deviation of the diode laser emitters on the bar from a straight line (”smile”) and for the alignment and the fixing of the lens.
- Aperture underfilling may also be a source for beam-quality reduction. Equation 2.1 only holds for the case of densely packed beams; In many cases, especially with ”classical” stacking techniques as displayed in fig. 2.4, it is difficult to avoid spaces between the beams, resulting in beam-parameter products, which are significantly larger than what results from equation 2.1.
- A further increase in the beam parameter product and thus a decrease in beam quality is introduced, if the individual beams in fig. 2.1 are not perfectly aligned in parallel. Misalignment angles of some mrad, which can not be avoided in many cases, may seriously degrade the beam quality of the total beam (cf. Fig. 2.6).

Current work is aiming towards raising these restrictions in order to closely achieve the line labelled ”equation 2.3” in fig. 2.5 by measures as:

- microoptical elements with higher optical quality and power throughput,
- diode laser bars and packaged elements with higher positional accuracy,
- diode laser bars with fast-axis divergence angles, which are lowered from NA=0.8 (enclosed power definition) to 0.5 - 0.6 by use of large optical cavities,
- new stacking concepts ensuring high filling factors and parallelism of the beams to be combined.

An approach for the latter concept (”optical stack”) is shown in fig. 2.6. The individual diode lasers are assembled not on top of each other as with ”classical” stacks but side by side on a step-shaped mounting base, the beams being combined by appropriate folding mirrors. This concept enables the use of thick, mechanically stable diode laser-submounts with low ”smile” and provides means for easy and precise parallel alignment of the individual beams. In fig. 2.7 the far-field emission pattern of an ”optical stack” with 8 diode laser bars is compared to that of a ”classical” stack. The comparison shows clearly the much lower height in the fast-axis direction of the total beam, caused by the additional degree of freedom in relative alignment of the individual beams.

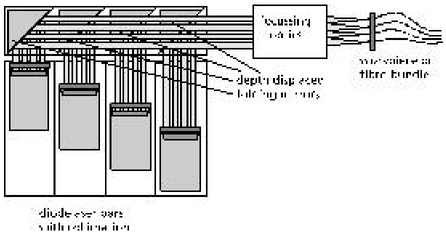


Fig. 2.6:

Principle of the ”optical stack”

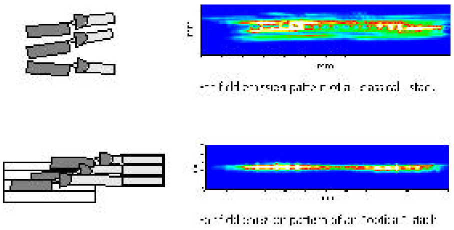


Fig. 2.7:

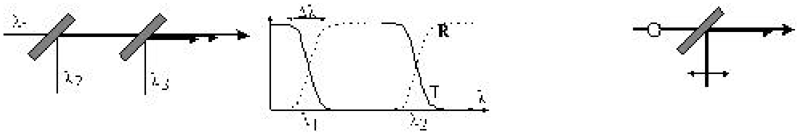
Far-field emission pattern of an ”optical stack” with 8 diode laser bars according to fig. 2.6 with a ”classical” stack as shown in fig. 2.4

As it is indicated in fig. 2.5 as well, it should be possible to shift the limit for diode laser systems considerably downwards to higher beam quality and to the right to higher output powers if modified system concepts and new semiconductor developments are integrated, which will be available in the near future. Integration of technologies as listed in the following will enable diode laser systems with output powers and beam qualities similar to those of present lamp-pumped solid-state lasers (line ”optimised systems” in fig. 2.5):

- Utilisation of diode laser bars with higher cw-output powers up to 50 W/bar and with
- Higher beam quality in the axis parallel to the p-n-junction (”slow-axis ”),
- Coupling of stacks with two polarisation states (cf. Fig. 2.8).
- Utilisation of ”wavelength multiplexing”: in most cases of materials processing the interaction process depends not or only weakly on laser wavelength, so that a couple of stacks or individual diode laser bars with different wavelengths can be coupled by appropriate elements as illustrated in fig. 2.8.

Fig. 2.8:

Principle of ”wavelength multiplexing” (left hand side of the picture) and ”polarisation multiplexing” (right hand side)



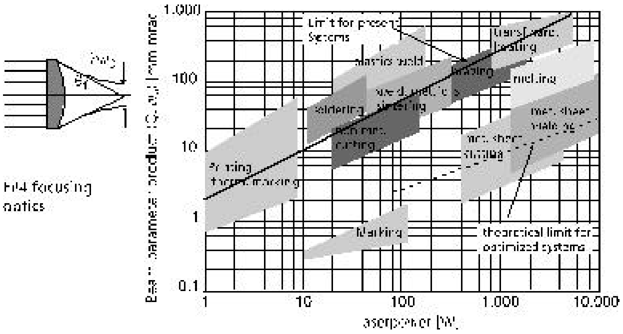
3. APPLICATIONS OF DIODE LASERS

In order to discuss and to compare the already existing as well as the potential range of materials processing applications for diode laser systems, a diagram similar to fig. 2.5 is used, however not showing the parameters of the laser systems but rather the requirements defined by the specific application. The basis for this discussion in fig. 3.1 are average laser powers and laser intensities at the workpiece which are necessary to perform the different indicated machining processes. These data have been converted into beam parameter products of a rotational symmetric beam, based on the assumption, that an F#4 focusing lens is used. As in fig. 2.5 the line for present diode laser systems as well as for systems optimised as discussed earlier is indicated.

With the optimised systems the large market for deep-penetration welding and cutting of steel sheets could be served in the future, however even with presently available systems many ”low intensity” applications can be performed as shown in the picture. All these applications can of course be carried out by conventional CO_2- and Nd:YAG-lasers as well. However, using diode laser systems is advantageous because these lasers are efficient, compact, easy to integrate into production lines, reliable and, at least in the near future, low-cost. The intention of the following examples is to illustrate what is already possible with diode lasers or even is already used in the production line.

Fig. 3.1:

Parameter ranges (average output power and beam parameter product) for common laser applications



Thermoplastics are materials which can ideally be welded by diode lasers due to their low melting point and low thermal conductivity, resulting in low demands to both required laser power (approx.10 - 80W) and focal spot size (approx. 0.5 - 3 mm). Both can easily be achieved with diode laser systems. In Fig. 3.2 typical welding geometries are compared, where a transmissive and an absorptive part are combined so that the laser-power is absorbed directly at the joining interface. In comparison to the competing technology, ultra-sonic welding, the strength of the laser joint is typically more than 50% higher. Fig. 3.3 shows an electronic key of a car, whose cover plate is welded to the case with diode laser already in the production line. By proper choice of the plastic compounds and pigmentation a joining geometry as shown in the upper part of fig. 3.2 has been achieved.

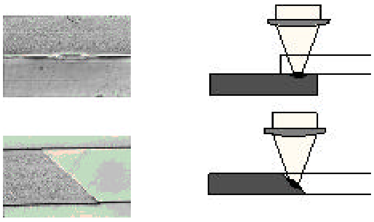


Fig. 3.2: Principle of welding of thermoplastics with diode lasers: a transmissive and an absorbing material is combined, so that the laser power is absorbed directly at the joining interface.

Fig. 3.3: Electronic car-key: The cover plate with the touch-pad has been welded to the case with diode laser (by courtesy of Marquardt Co.)

Soldering of electric and electronic components as shown in fig. 3.4 and 3.5 are further examples, where diode lasers are already employed or will likely be used broadly in the neat future due to the mentioned advantages of these lasers.

Fig. 3.4: Soldering of SMD chips with diode lasers

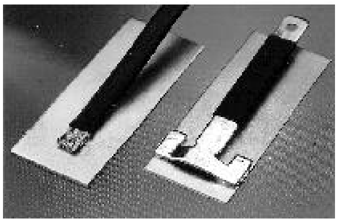


Fig. 3.5: Soldering of electric connecting braids with diode lasers for the autometive industry

4. SUMMARY AND OUTLOOK

Beside the utilisation of high power diode lasers for the pumping of solid-state lasers the direct application of diode lasers is attracting growing interest in the past few years due to the principle advantages of diode lasers such as efficiency, compactness, simple integratebility into production lines, reliability and, at least in the near future, low-costs. The technique of incoherent beam combination is a straightforward way to build the required diode laser systems with output powers ranging presently from 10 W to approx. 1.5 kW. Such systems are currently entering the market for industrial production tools, examples of the related applications such as welding of plastics and soldering have been discussed in the paper. Despite the advantages of diode lasers in such ”low-intensity” applications, the full application range of present CO_2- and solid-state lasers can not be covered by diode lasers due to beam quality restrictions of present systems. As it has been discussed in the paper it is however in principle possible to build diode laser systems in the kW-range with beam qualities comparable with present lamp-pumped solid state lasers and thus mass-applications as deep-penetration welding or cutting of steel can be served with diode lasers directly. The author believe, that such systems will be available within the next 3 years and will open large new markets for diode lasers in particular and for industrial laser materials processing in general.

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