Brightness and average power as driver for advancements in diode lasers and their applications *(Invited Paper)*

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ABSTRACT

Spatial and spectral emission characteristics and efficiency of high-power diode laser (HPDL) based pump sources enable and define the performance of the fundamental solid state laser concepts like disk, fiber and slab lasers.

HPDL are also established as a versatile tool for direct materials processing substituting other laser types like CO_2 lasers and lamp pumped solid state lasers and are starting to substitute even some of the diode pumped solid state lasers. Both, pumping and direct applications will benefit from the further improvement of the brightness and control of the output spectrum of HPDL.

While edge emitting diodes are already established, a new generation of vertical emitting diode lasers (VCSELs) made significant progress and provides easy scalable output power in the kW range. Beneficial properties are simplified beam shaping, flexible control of the temporal and spatial emission, compact design and low current operation. Other characteristics like efficiency and brightness of VCSELs are still lagging behind the edge emitter performance.

Examples of direct applications like surface treatment, soldering, welding, additive manufacturing, cutting and their requirements on the HPDL performance are presented. Furthermore, an overview on process requirements and available as well as perspective performance of laser sources is derived.

Keywords: high-power diode lasers, direct diode lasers, simulation technology, laser applications, process regimes, additive manufacturing

1. INTRODUCTION

Laser systems based on edge-emitting diode lasers are established in in a wide range of applications from lighting technology to materials processing like soldering and welding and show the potential to substitute solid state and fiber lasers in cutting and deep penetration applications. These applications have different requirements in power, as well as spatial and spectral properties of the laser emission. Concerning spatial and spectral brightness, high power diode lasers range between LEDs and solid state lasers. They show the best efficiency of all known laser sources concerning conversion of electrical power into optical power. Electro-optical conversion efficiencies of about 75% have been demonstrated by different research groups. In parallel to these improvements main activities focused on the extension of reliability and life time. While for most medical lasers some 100 hours of operation are sufficient, industrial lasers require reliable operation over several 10.000 hours.

Besides the diode laser systems based on high-power edge emitters, another type of diode lasers based on vertical emitters (VCSEL) has made significant progress in the past few years. Power scaling to multi-kW level and a significant improvement in efficiency have been achieved. VCSELs have been demonstrated at multi 100 W output power out of arrays of single emitters by Princeton Optronics and Philips U.L.M Photonics.

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The increase in output power and brightness is a main driver of the expanding range of direct HPDL applications. The improvements of the diode laser performance has been driven by optimization of manufacturing processes, reduction of losses of the semiconductor materials allowing for better heat removal by longer resonators and improved facet coating processes. Packaging is another important factor for optimization of diode laser performance by improved heat sink configurations and expansion matched heat sink materials allowing for low stress Gold-Tin soldering of diode laser bars.

2. VERTICAL EMITTERS AND EDGE EMITTERS

Low power **edge-emitters** have been developed in the 1980s with a focus on communication and data storage applications. In the 1990s the power of laser bars reached more than 20 W and lifetimes of more than 10.000 h. The manifold advantages of pumping solid state lasers with diode laser radiation and improvements of the GaAs crystal-growth technology pushed the development.

Today, almost all commercial edge-emitters base on a separate confinement heterostructure (SCH). The quantum well layers (*Figure 1, No. 10*) are embedded in the waveguide (*Figure 1, No. 9a, 9b*) and cladding layers. Therefore, the optical confinement and the recombination area (with a height of a few tens of nanometres) are separated.

There are many variations of asymmetry, location and thickness of the layer structure to influence the vertical mode field, the efficiency and the threshold current. The layer structure is grown on an n-doped substrate (*Figure 1, No. 8*) and after processing the contact windows, the p- and n-contacts are gold plated (*Figure 1, No. 7 and 12*). Typically, the mode field diameter of the vertical eigenmode of the waveguide is in the region of 1 µm. Because only the fundamental eigenmode is amplified ($M^2 \approx 1$), the beam quality in vertical direction is almost diffraction limited and the (full) angle of divergence ranges between 26° and 100°.

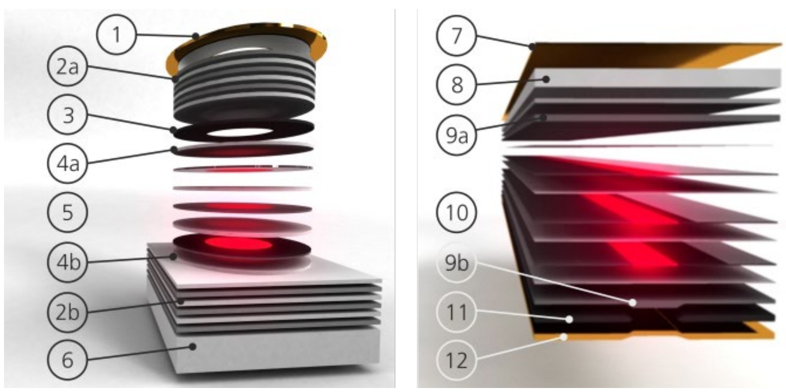

Figure 1: Scheme of the epitaxially grown layer structures of a vertical emitting diode laser (left) and a broad area edge-emitter (right). [1]

In contrast to the well-defined eigenmode in vertical direction, the lateral nearfield of a broad area edge-emitter with a typical lateral injection current width of 50 - 400 µm shows high-power filaments alternating in the timescale of several resonator round trips. Moreover, the lateral nearfield intensity distribution changes due to temperature, current density, intensity and feedback. The lateral angle of divergence is a function of the injection current and usually increases at higher currents. At present, efforts aim at a reduction of the lateral angle of divergence to ≈ 6°. Typical characteristics of a commercial NIR single edge-emitter are listed in *Table 1*.

Table 1 Characteristics of a NIR single edge-emitter with a lateral width of 90 µm. [2]

Wavelength λ	940 nm	Divergence θ_V	55°
Power P	12 W	Divergence θ_L	11°
Threshold current I_{th}	0,3 A	Spectral width $\delta\lambda$	4 nm
Beam quality M_V^2	1,1	Spectral drift $\partial\lambda/\partial T$	≈ 0,3 nm/K
Beam quality M_L^2	14	Efficiency @ P_{max}	61 - 63 %

Some basic requirements result from the asymmetrical beam quality and the true multimode behavior along the lateral direction:

• anamorphic optics design is necessary,

• acylindrical fast-axis collimation lenses are required,
• homogeneous intensity distributions (e.g. a constantly illuminated line) require homogenization optics.

Vertical-cavity surface-emitting laser diodes (VCSELs) were first suggested in 1977 by Professor Kenichi Iga [3] and demonstrated in 1979 [4]. Since the 1980s they have become very popular in low-power applications like datacom or sensing due to their high reliability and low-cost production [5]. High-brightness fiber-coupled modules based on VCSELs (e.g. 30 W, 50 µm, NA 0.2) have been demonstrated since 2010 [6].

The vertical cavity is formed by two multi-layered DBR areas (Distributed Bragg Reflector, *Figure 1*, *No. 2a*, *2b*) which typically consist of 20 to 40 layers forming Volume Bragg gratings. Depending on the modefield diameter and the application, VCSELs are fabricated to emit either through the n-doped substrate (*Figure 1, No. 6*) or from the top surface of the p-contact (*Figure 1*, *No. 1*). In between the DBR sections the active layer with up to three quantum wells is placed with a thickness of 8 nm – 50 nm (*Figure 1, No. 5*). Between the active layer and the Bragg reflector, the inner p- and n-cavities (*Figure 1, No. 4a, 4b*) adjust the total cavity length so that a maximum of the longitudinal mode coincides with the center of the active layers. The cavity length is of the order of the wavelength and due to the small diameter of the cavity the active volume is up to three orders of magnitude smaller compared to edge-emitting devices. The reflectivity of the DBR section is ~ 99.9 % and 99 % to provide the feedback for sufficient gain and efficient laser operation. In a rough approximation, the threshold current is proportional to the volume of the active region and therefore the threshold current is also up to three orders of magnitude lower compared to edge-emitting devices.
The oxide aperture (*Figure 1, No. 3*) directs the current flow. The size of the aperture close to the active layer defines the pumped region and therefore the mode field diameter. Alternatively, the optical confinement can be set up by gain guiding, index guiding (buried heterostructure) or anti-guiding [3].
A single VCSEL is fabricated with a diameter of the oxide aperture between 3 µm (SM) and 300 µm. A rich dynamic in the angular emission profile for large-area VCSELs is observed if the aperture increases [5]. The corresponding Fresnel number of the multimode cavities is in the region of 10^2 - 10^5. A typical VCSEL which is fabricated for a densely arranged array emits up to 5 mW (*Table 2*).

Table 2 Characteristics of a multimode NIR VCSEL emitter integrated in an array (Philips Photonics)

Wavelength λ	808 nm	Divergence $\theta_V = \theta_L$	≈ 20°
Diameter d	8 µm	Spectral width $\delta\lambda$	≈ 1 nm
Power P	≈ 1 mW	Spectral drift $\partial\lambda/\partial T$	0,07 nm K^{-1}
Threshold current I_{th}	1 mA	Efficiency η_{max}	50 %
Beam quality $M_V^2 = M_L^2$	5		

Besides the vertical emission from the substrate, VCSEL structures provide a variety of advantages with regard to an application in the field of materials processing:

- very low threshold current,
- insensitive spectral emission to temperature changes,
- high speed modulation,
- monolithic production process,
- densely arranged 2D-arrays with high fill factor and customized intensity distributions,
- testing on wafer level and finally
- comparatively cost efficient package and mounting.

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3. POWER SCALING CONCEPTS

In the field of high-power semiconductor lasers, the scaling of output power is performed by (1) spatial stacking and fiber multiplexer in case of fiber-coupled beam sources, (2) polarization multiplexing, (3) dense wavelength division multiplexing, (4) coarse wavelength division multiplexing. In combination with edge-emitters, all of the multiplexing technologies are used to achieve a high brightness. In contrast, commercially available VCSEL-systems include only spatial stacking on behalf of low costs. The aggregation of several multimode edge-emitters to bars and stacks or either to modules which include an optical stack of single emitters is well established (*Figure 2*, *step 1-3*). Moreover, wavelength multiplexing enables to perform applications like key hole welding with direct diode laser modules (see section “Process regimes”). During the last years, the spacing between the center wavelengths of the combined emitters or bars has decreased and dense wavelength multiplexing has been shown with center wavelength spacings ≤ 3 nm [7]. Either external cavities for simultaneous wavelength-stabilization and wavelength-multiplexing [8] or two-step procedures including a wavelength-stabilization and a separated multiplexing unit [9] are promising approaches. Using Volume Bragg Gratings as frequency filters, the Fraunhofer ILT demonstrated dense wavelength division multiplexing of diode laser radiation with efficiencies between 85% and 97% depending on the beam quality of the input beams [10][11]. Thereby, the spectral spacing between adjacent wavelengths is only 1.5 nm.

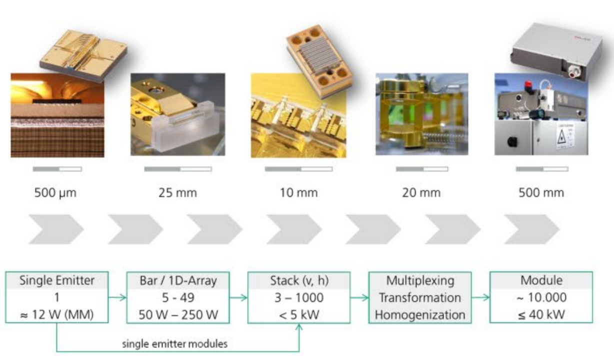

Figure 2: Power scaling of edge-emitters. [1]

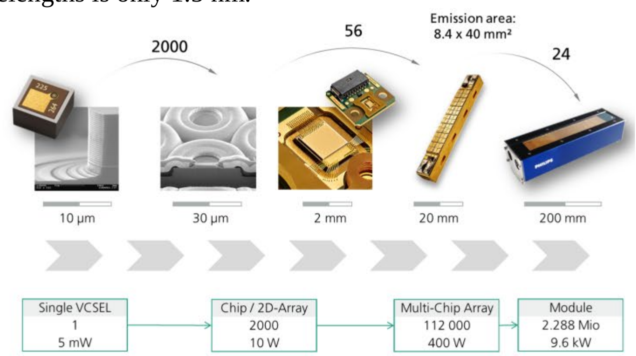

Figure 3: Power scaling of VCSEL emitters. [1]

As already mentioned, scalability and the very uniform irradiation patterns are the main advantages of VCSEL systems. Concerning the spatial arranging of VCSEL emitters, wafer-scale production and the building block approach on all levels of assembly are advantageous. The VCSEL modules manufactured by Philips Photonics have been arranged as follows (Figure 3):

1. At first, a densely packed VCSEL array is separated from the wafer. On one chip with a footprint of 4 mm² there are ≈ 2000 of the Ø8 µm VCSELs arranged [12].
2. The next packaging step contains 56 of those chips mounted on a heat sink to form one stack with an emission area of 8.4 x 40 mm². The electrical connections of the arrays can either be fabricated in parallel or in series [12].
3. Those stacks are afterwards connected to modules with up to 9.6 kW output and an emission area of 209 x 40 mm² [12].

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4. PROCESS-ADAPTED INTENSITY DISTRIBUTIONS

High power edge emitters offer extremely high efficiencies and very compact size (*sec. 2. Vertical emitters and edge emitters*). By stacking these devices, multi-kW output powers can be achieved which is suited for many applications (examples are given in *sec. 6*). As a major drawback, this yields typically to very asymmetric intensity profiles which are highly depending on the devices used. Furthermore the beam quality in the lateral and vertical direction differs significantly. To overcome these drawbacks, the output beam of the diode laser source is usually shaped by optical setups to a desired intensity distribution.

One common intensity distribution which is advantageous for many applications is the rectangular distribution, also called tophat intensity distribution, and this shape is generated by homogenization optics. Either one direction – usually the slow (lateral) axis – or both directions can be homogenized. The reliability of the diode laser system can be increased by homogenization as the intensity distribution remains unchanged if single devices fail. The optical setup consists of the following components:

1. If a nearly symmetric beam quality is demanded, a beam transformation device is used to adapt the beam quality of the fast and slow axis. This is usually necessary if a squared area with comparable angles of divergence for fast and slow axis has to be illuminated. One frequently used device for performing the beam transformation is the so-called microstep mirror. This device divides the beam in the slow axis direction in a number of sub-beams and rotates each sub-beam by 90°, thus resulting in an adaption of the beam qualities [13].

2. Next, the beam dimensions are adapted to the entrance aperture of the homogenizer by using anamorphic optics.
3. The homogenizer divides either the far field intensity distribution and overlays the sub-apertures in the exit plane of the homogenizer by multiple total internal reflections (light pipe) or the near field intensity distribution by using one or two microlens arrays and a field lens to overlay the sub apertures in the image plane [14].
4. For the light pipe homogenizer, the exit plane is usually imaged on the work piece. If the fast axis is not homogenized, it is focused on the work piece to increase the intensity.

Typical applications for homogenized diode laser systems include transformation hardening of metals, polymer welding, illumination, and laser-assisted thermoplastic tape laying. In *Figure 4*, a diode laser system developed for simultaneous hardening of guiding rails is shown. Each module irradiates the contact area of the ball and guiding rail, the slow axis is homogenized, while the fast axis is focused on the work piece (*see Figure 5*). The standard deviation of the homogeneous intensity distribution in the slow axis direction amounts to 0.78%, and the spot measures 640 µm (fast axis, full width 1/e²) x 5.1 mm (slow axis, full width at half maximum). Another challenging example is the uniaxial homogeneous intensity distribution required for the pumping of a slab laser medium (*Figure 6*) [15]. Due to the homogenous thermal load, an almost aberration-free thermal lens is induced inside the slab crystal. The vertical beam height shown in the false-color intensity plot (*Figure 6*) is 200 µm and the width about 6 mm.

Figure 4: Diode laser system developed for simultaneous hardening of linear guiding rails.

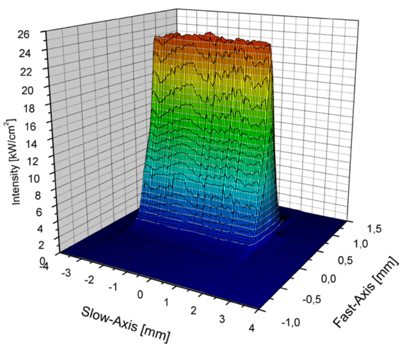

Figure 5: Intensity distribution of one module of the diode laser system for hardening at the work piece.

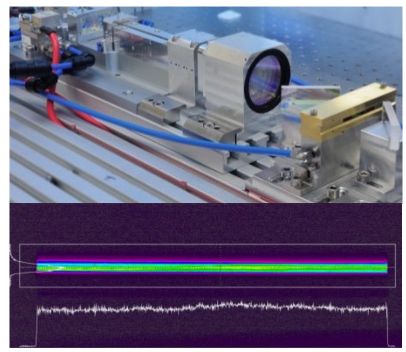

Figure 6: Pump optics of a slab laser and measurement of the pump intensity distribution: 200 µm beam height and 6 mm width.

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5. BRIGHTNESS ENHANCEMENT BY SIMULATION TECHNOLOGIES

5.1 Vertical Emitters

A promising concept for the realization of high brightness surface emitting lasers is the V**E**CSEL, which has been studied intensely at Fraunhofer ILT in collaboration with Philips Technologie GmbH Photonics. By means of external optics (usually a spherical mirror) the VECSEL allows for the combination of the high output power known from large-area VCSELs with the excellent beam quality (ideally fundamental mode operation) of conventional lasers which comprise resonators with small Fresnel numbers. In order to identify crucial effects limiting the efficiency of single-mode VECSELs, a model has been developed to predict the L-I characteristics and the modal decomposition of electrically pumped VECSELs in dependence upon the heterostructure design and the external cavity configuration. A description of the model is presented in [16]. In close cooperation with accompanying experimental work, the tendencies observed in the laboratory, or favorable resonator geometries in dependence upon the quality of the epitaxial material, could be understood. In addition, a central design criterion could be identified for dielectric layers for lateral current confinement (oxide aperture) with good optical properties in VECSELs. Subsequent to the cooperation, the output power of the single mode VECSELs from Philips Photonics could be increased by a factor of four. For experimental results on the laser performance of current Philips VECSELs see [17].

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5.2 Edge Emitters

When high-power diode lasers are used for coherent or incoherent beam superposition and for pumping of solid-state lasers, the requirements upon them are high power and spectral stability in combination with spectral line widths of < 1 nm. Non-linear effects, such as thermal refraction index variations and refractive index variations induced by the presence of charge carriers, lead to filamentation of the light field. The beam quality strongly depends on these thermal- and carrier-induced nonlinearities which lead to instable operation of the device and a filamented optical field in the lateral direction due to self-focusing and self-defocusing effects. [18]

Furthermore, the central wavelength drifts about 0.3 nm/K with the temperature and correspondingly with the injection current. To reduce the shift of the wavelength and the spectral width which both depend on the point of operation, in many diode laser modules Volume Bragg Gratings (VBG) are installed in external resonators to reflect a fraction of the radiation emitted from the diode laser back into the waveguide. Based on passive optical wavelength stabilization the drift is decreased to 0.01 nm/K and the spectral width is reduced to 0.2 - 0.4 nm (full-width half maximum, FWHM) [19]. According to the state-of-the-art the specific parameters of the external system for spectral stabilization are determined in experiments.

Software solutions have been developed at Fraunhofer ILT for the simulation of diode laser edge emitters and micro-optics, such as Volume Bragg Gratings and aspherical collimation lenses. The software package enables the analysis of innovative micro-cavity lasers with external resonators for longitudinal or transversal mode selection. Goal of the numerical analysis is to support the design process of external feedback systems and semiconductor devices, and thus lead to shorter design cycles and reduced development costs.

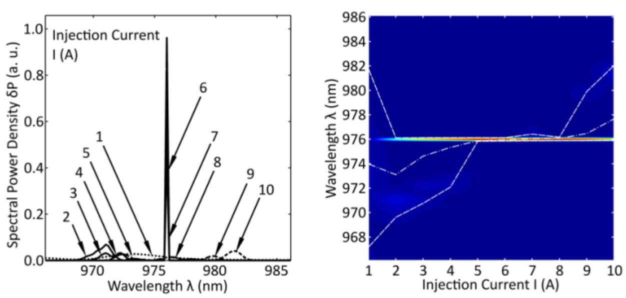

Figure 7: Calculated spectral stabilization with external reflectivity of 6%:normalized spectral power density (left) and spectral map in false colors with 90% power inclusion and central wavelength (right). [20]

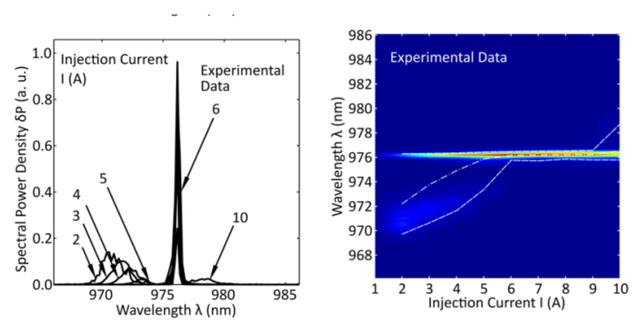

Figure 8: Measured spectral stabilization with external reflectivity of 6%:normalized spectral power density (left) and spectral map in false colors with 90% power inclusion and central wavelength (right). [20]

The multi-frequency 2D cross section laser model includes solvers for the transverse electrical, thermal and optical fields with attached external resonators for transverse and longitudinal mode selection [20][21]. The goal is to calculate the dynamics of the electromagnetic field in diode laser edge emitters with coupled frequency-selective external resonators. The frequency domain model is implemented in MATLAB and Python software packages for numerical simulation of HPDLs together with micro-optics, such as Volume Bragg Gratings (VBG) and aspherical collimation lenses (Fast-Axis Collimation, FAC) and lens arrays (Slow-Axis Collimation, SAC). Internal device properties such as local temperature, carrier density and the photon density are iteratively calculated to account for the interaction between the semiconductor material and the light field. In the developed model, light-, temperature- and charge carrier-distributions are computed in a Fox-Li like iteration scheme for transverse slices along the semiconductor hetero-structure by use of wide-angle finite-difference beam propagation. Depending on the operating current, the laser characteristics are evaluated numerically, including near- and far-field patterns of the astigmatic laser beam, optical output power and the emission spectra, with central wavelength and spectral width. The focus of the model lies on the prediction of influences on the spectrum and power characteristics by frequency selective feedback from external optical resonators. Problem specific solvers with reduced complexity predict the effects of external feedback on the emission spectrum, optical output power and near- and far-field distributions. Simulation results and measurements of a spectrally stabilized diode laser are in good agreement (compare *Figure 7* and *Figure 8*).

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6. DIRECT DIODE LASER APPLICATIONS

6.1 Additive Manufacturing – Selective Laser Melting

Within the rapidly growing field of “digital photonic production” customer‘s demands are an increase of productivity and scalability. That implies increased build-up rates, customized building chambers and installed laser power. There are multiple fundamental approaches to develop fast SLM machines for series production:

1. Movable scanning fields result in high requirements regarding the position accuracy and unfortunately do not result in an increased build-up rate.
2. Multiple scanning fields are more cost-intensive and furthermore a complex process strategy is required in areas of overlapping scan fields.
3. Higher laser powers may offer increased build-up rates, but thermal strain limits the absorbed power, and a process development for higher laser powers has not been completed yet.

Figure 9: Lightweight constructions manufactured by SLM.

A promising approach which is developed and tested by the Rapid Manufacturing Research Group at the Fraunhofer ILT is to use a fixed array of multiple spots simultaneously in a “print head” moved by a gantry system of linear axes. Several high power diode lasers create a controllable intensity distribution and therefore allow for manufacturing 3D structures with high flexibility in terms of productivity and building space. Although one might suppose to use a VCSEL array, the required radiance for melting metal powder with a suitable feed rate is higher by three orders of magnitude compared to the technically feasible radiance of VCSEL. The local temperature for melting metal powder must be in between 1400°C and 2400°C depending on the material. In regard of suitable working distances and spot diameters of approx. 100-200 µm, the beam parameter product has to be **≤ 10 mm mrad** at a continuous output of approx. **200 W**. Thus, this application is currently restricted to diode laser sources based on edge-emitters. We expect SLM approaches using VCSEL in the near future.

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6.2 Additive Manufacturing: Wear protection – Laser Metal Deposition to improve forging tool life

In the application field of forging, the form-giving tool components are subject to process-related severe environmental conditions, such as high mechanical loads acting simultaneously with high tribological and thermal charges. Due to high machine hour rates as well as increasing environmental requirements in terms of energy consumption, wear protection methods and suitable repair measures for forging tools become more and more important.

Laser Meal Deposition (LMD) represents an established process for the repair of complex shaped surfaces. A new approach is the addition of nano-sized high melting particles to improve the mechanical properties. The main idea is to reduce the grain size of the deposited layers by adding nano-sized nuclei. A fine grained microstructure will improve strength as well as ductility and fatigue resistance. Furthermore small hard particles can improve the wear resistance without affecting the friction of the surface. Ball milling of a mixture of the matrix powder material and nanometer-scaled additions of WC (60 – 120 nm) was performed in a high-energy planetary mono-mill to prepare nano composites which are suitable for a conventional powder feeding system. A **3 kW diode laser** with a wave length of 976 nm and a beam parameter product of **100 mm mrad** is used. Defect free layers (without cracks, density > 99.5%) were clad with contents of nanoparticles from 0.05 up to 2.5 wt.-%. The hardness of the layers is increased from 650 to over 800 HV for

2.5 wt.-% addition whereas the mechanical properties are similar to not reinforced layers due to the fine grained structure. In a real forging test with a mock-up geometry several hundred parts were forged and the reinforced layers showed an increased wear resistance. Investigations on field tests are on-going. Especially a post heat treatment to improve the layer performance is under consideration.

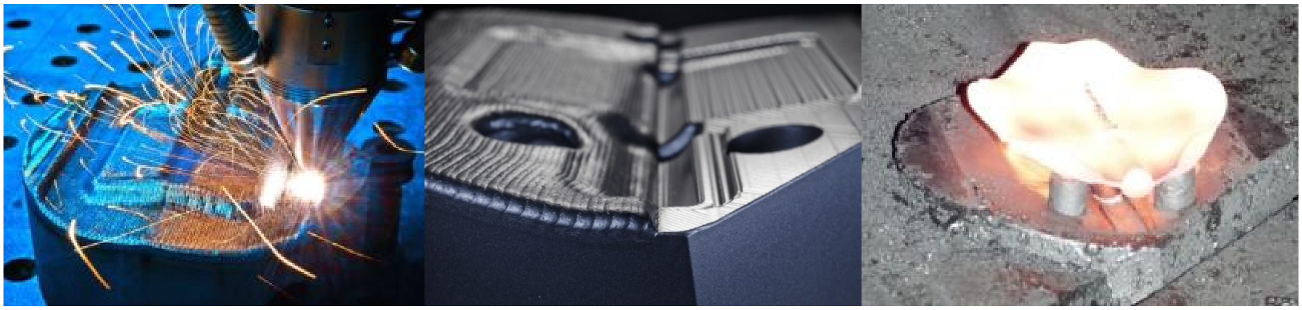

Figure 10: LMD process of a forging die (left), die with deposited layer (middle), forging process (right).

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6.3 Automotive industry – laser-treated steel LTS

Lightweight construction is an effective method for reducing fuel consumption and CO_2 emissions in the automotive industry. At the same time, crash safety specifications are constantly being tightened. The use of thinner but stronger high strength steel especially for crash relevant parts is an effective option to meet both requirements. With hot stamping, complex geometries can be formed, while high strength is achieved when the part is hardened in a cooled die. In the case of the widely used Manganese Boron Steel 22MnB5, the tensile strength is 1600 MPa after hot stamping. Such high strength is not desired in the whole part. Deformation zones for better crash performance and zones for joining require a more ductile material. The LOKWAB project, which was funded by the German Federal Ministry of Education and Research (BMBF), has been investigating local heat treatment of hot stamped parts with laser radiation. The aim was to soften the desired zone of hot stamped parts to improve crash performance and subsequent joining operations.

In order to realize the heat treatment process, at the Fraunhofer ILT a temperature-controlled fiber-coupled **12 kW** diode laser with a BPP of **100 mm mrad** and zoom-optics forming a rectangular spot size up to 52 x 52 mm² are used. The homogenization system contains two independently controllable zoom homogenizers which enable changing the spot size in x- and y-direction during operation. The adjustable spot size also allows softening of small zones down to 10 x 10 mm² e. g. for joining by spot welding. Usually, with NIR laser power between **200 W and 10 kW** feed rates from 0.1 to 1 m/min can be achieved. [22]

As an example, in the heat treated zone of a B-pillar (*Figure 11*) the micro structure is changed (tempered of the martensite or austenitization followed by transformation to ferite/pealite) which results in an increase of the breaking elongation from 4 % to 19 %. A heat treatment strategy was developed to minimize distortion. With an adapted strategy the maximum distortion of a local heat treated B-pillar was reduced from 10 to 1.7 mm. The corrosion protective AlSi-coating of the parts is not affected by the laser heat treatment. Using maximum laser power, a processing rate of up to 15 cm²/s is achieved.

Furthermore, tensile tests of the dual-phase steel Docol 1200 show a reduction of tensile strength from 1158 MPa to 603 MPa while uniform elongation is increased from 4.6 % to 17.1 %. By choosing appropriate process parameters, mechanical properties within the mentioned range can be set. By the local heat treatment with laser radiation, formability of steel sheets is to be improved in critical areas. This allows more complex geometries to be formed in a subsequent cold forming process.

The newly developed process based on diode laser radiation paves the way for material and component-tailored solutions for local laser heat treatment of sheet metals above and beyond softening (tempering, recrystallization, hardening). Graduated properties can also be produced across the sheet metal thickness. Regarding the commercial aspects, in the case of small softening areas, the laser technique proved superior to conventional techniques, especially where flexibility is required.

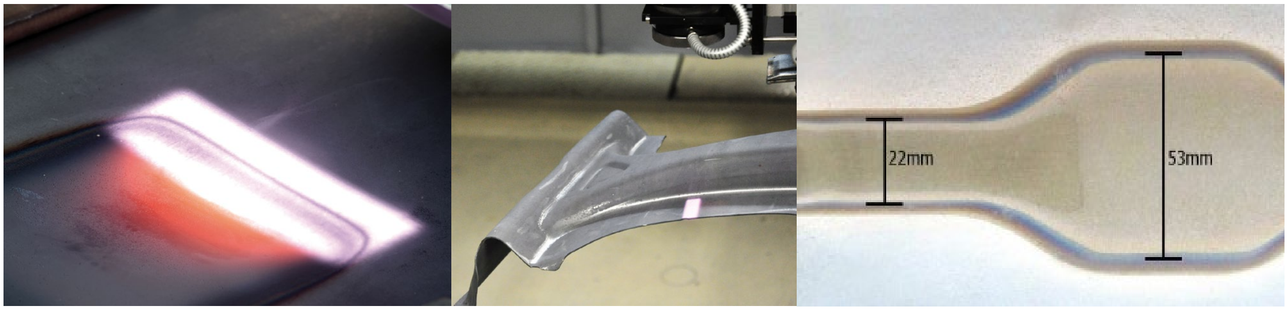

Figure 11: Local heat treatment with rectangular laser beam profile (left), local laser heat treatment on a B-Pillar (middle), heat treatment with variable track width (right).

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6.4 Laser in Photovoltaics

In order to produce silicon solar cell modules, the prefabricated solar cell wafers are joined in series by the means of interconnectors. Copper interconnectors with a thickness of 150 µm coated with 18.8-25 µm SnAg4 solder are joined on the silver glas frit contact pad of the solar cell over a length of 140 mm in a soldering process. Conventional processes are hot air soldering, infrared soldering or thermode soldering. In order to achieve a process cycle time below 2.5s/solar cell, soldering processes with a minimal process time and a low thermo-mechanical stress induction are required [23]. The high-power laser source LDM3000-100 from Laserline with a beam quality of **100 mm mrad** in combination with a line-generating optic shapes the laser beam into a geometry of 140 mm x 2 mm in the focus plane, covering the complete joining zone *(Figure 12).*

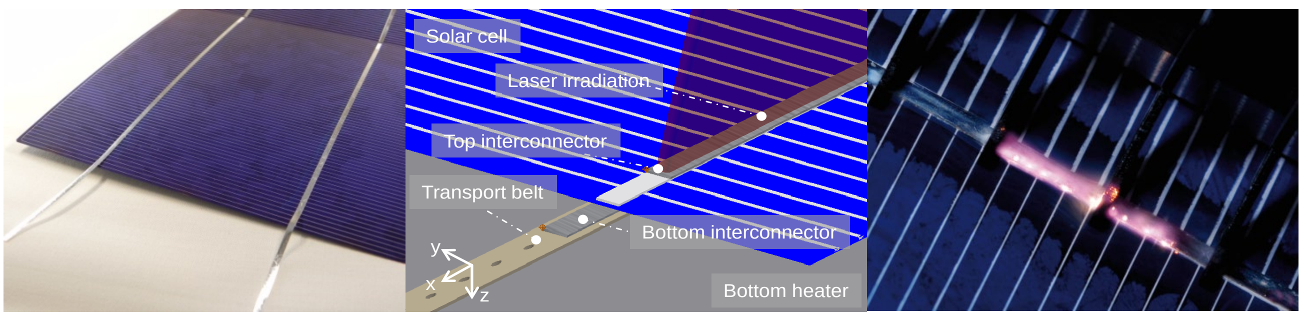

Figure 12: Joined interconnectors on solar cell (left), schematic of laser soldering process with line-generating-optic (middle, [23]) and photo of the soldering process (right).

The simultaneous energy deposition with the line-generating optic enables to lower the process time down to 0.2s/interconnector for a laser power of 1800 W. [23] However, the short process time leads to an increase of the crack occurrence measured by 180°-peel tests. The lowest process time without increase of the crack occurrence in the joining zone is 1 s/interconnector at a laser power of **510 W**. A further process optimization by ramping of the laser power in the cooling down phase can potentially lead to a further minimization of the thermo-mechanical stress. A concept with a multi-line optic enables to reach this process time for multiple interconnectors on the solar cell.

Alternative process approaches consist of a quasi-simultaneous energy deposition with a scanner and the laser source LDM200-500 (BPP = **20 mm mrad**). With a laser power of **460 W**, a velocity of 3200 mm/s and 25 repetitions, the repetitive scanning joining zone enables a sequential local energy deposition. By division into quasi-simultaneously soldered segments the repetitive scanning lowers the absolute thermal expansion and therefore stress occurrence. This increase in temperature control and geometric flexibility is however compensated with a process time increase compared to the application of a line-generating optic.

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6.5 Soft-soldering

The joining of sensitive SMD-components on PCB-substrates is conventionally realized by solder processes. The laser soldering process is established in the application field of the joining of temperature and pressure sensitive components with high package density, where conventional soldering methods are not applicable. Depending on the enameled wire isolation class, the contact free and locally limited energy deposition by laser enables an interconnection of enameled wire to PCB contact pads without prior removal of the enamel. The laser soldering process is mainly applied with solder wire with flux core, but can also be applied with preforms or solder paste. However, the direct laser irradiation of solder paste requires an adjustement of the time-temperature profile to prevent an instant flux evaporation, which can lead to spatters. The laser power for contact areas of ~5-10 mm² is usually in the range of up to **50W**, irradiated by a diode laser source with low beam quality (beam quality **30 mm mrad**) and a focus diameter of about Ø 0.5 – 1 mm.

The main task of the laser process development is the coordination of the solder core wire feed (*Figure 13* middle) to the laser power profile, in order to achieve a high wetting angle of the solder. By customizing the laser focus diameter and solder wire diameter to the contact area, the laser soldering process enables a locally controlled temperature distribution.

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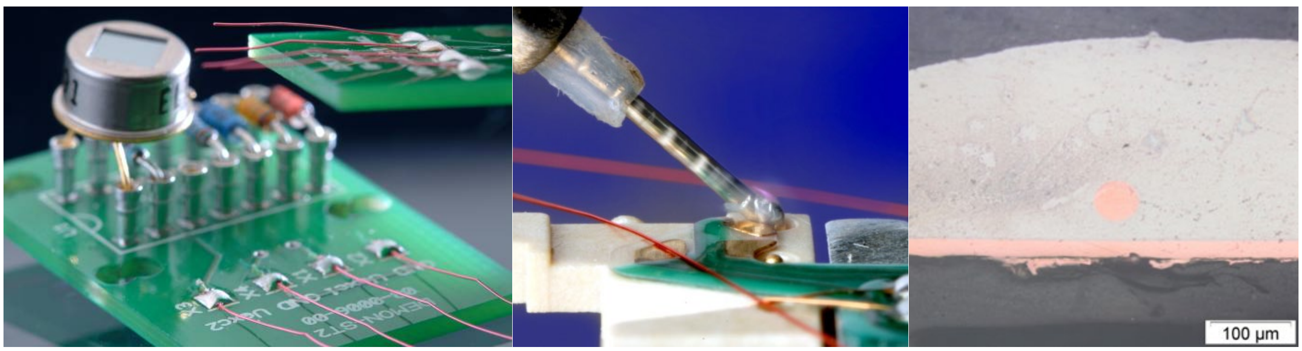

Figure 13: Laser soldered enameld copper wire on PCB contact pad (left [24]), joining process with solder core wire feed (middle) and cross section of the solder connection (right).

6.6 VCSEL Illumination for Process Observation

Camera based process observation and process control requires access to characteristic features that qualify the operating-point or the final product quality. For laser-based manufacturing-processes, this can either be achieved by detecting the emission of the process or by detecting characteristic properties of the process zone where the laser beam interacts with the material and the surrounding area of the work piece. To acquire that information, an external illumination is needed for the imaging system to deliver images which can be processed by computer vision algorithms [25]. Important properties of such illumination systems for process observation in manufacturing can be listed as

- Intensity in the observed area that enables short exposure times
- Small size of the light delivery system that is attached to the processing head to ensure applicability in the industrial environment
- Light properties such as suitable wavelength, low coherence and small bandwidth to conserve information content of the image

Illumination sources for process observation are mostly used in the near infrared region at about 800 nm. At this wavelength, the sensitivity of standard CMOS camera systems is still acceptable and the available radiation sources provide considerable optical power. Three different solutions can be considered as suitable illumination sources: laser diodes, LEDs and VCSELs. An overview of the characteristic properties of the three possible illumination sources is given in *Table 3*.

Illumination for process observation ideally is mounted in the vicinity of the interaction zone, making the processing head a preferable candidate for the integration. In this environment, space is limited what makes the light source’s the intensity per area a primary objective.

Table 3: Characteristic properties of different illumination sources.

Properties (without application specific optics)	LED	Diode Laser	VCSEL
FWHM bandwidth	45 nm	2 nm	2 nm
Optical power (typ.)	0.2 W	35 W	4 W
Etendue	$3.14\ 10^{-6}$ m²	$1.95\ 10^{-4}$ m²	$2.3\ 10^{-5}$ m²
Emission cone	170°	24°	17°
Emission Area	1 mm²	Ø = 400 µm	2 x 2 mm²
Conversion efficiency (el.→opt.)	0.11	0.43	0.3

The VCSEL technology has the advantage of a laser source in terms of light-ray-delivery and optical power and the advantages of LEDs in terms of installation space and low cost solution. On a surface of two by two millimeters, this illumination source provides more than 2,000 laser emitters. Each of these emitters has a cone angle of about 17° resulting in an emission with a numerical aperture of 0.15. All 2,000 emitters have a bandwidth of about 2 nm which is comparable to that of a single laser diode. In sum, one VCSEL device with 2,000 emitters provides an output of **4 W** of optical power at a conversion efficiency of 30%. This makes it an ideal device for illuminating areas which are larger than the emitter itself, up to applications where the full field of a scanning system needs to be observed. As there is only a limited need for beam guidance, VCSELs can be arranged as a set of sources. This provides a scalability of the intensity on the work piece and guaranties a directional independent illumination as objects are illuminated from different angles.

Fraunhofer ILT has developed a special illumination module for the industrial brazing optics ALO3 from Scansonic MI GmbH, see *Figure 14*. It consists of eight VCSEL devices, emitting 32 W of optical power to illuminate the processing zone. In combination with a coaxially integrated high-speed camera a powerful process observation system has been realized that is suitable for acquiring images of high quality in series production with more than 300 images per second. An example of the resulting process images is given in *Figure 15*; brazing wire, melt pool as well as the solidified seam are visualized. The image quality is more than sufficient to run computer vision algorithms that measures machine parameters like brazing velocity as proposed by [26] that can be used for controlling purposes. In addition, the process observation gives the opportunity to evaluate the product quality during manufacturing in terms of on-line pore detection [27].

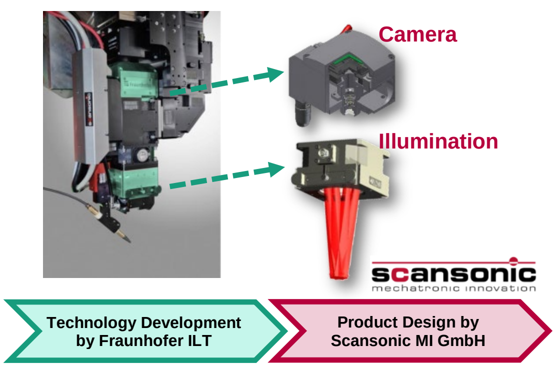

Figure 14: On the left a functional model of the process observation system; on the right the industrial implementation of camera and VCSEL-illumination module.

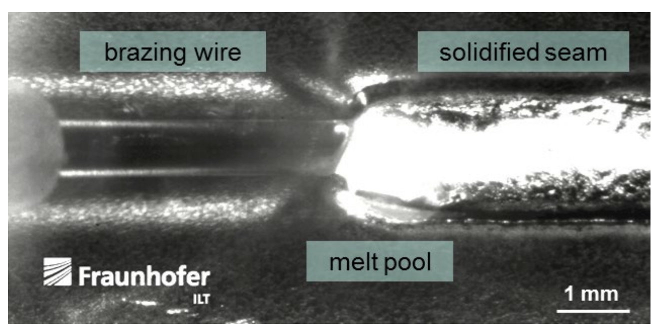

Figure 15: Process observation during laser brazing.

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6.7 Plastics Welding – Hybrid connection of plastic and metal

Bonding of heterogeneous working materials is an important requirement, especially for lightweight construction in the automotive industry. One big challenge to enable lightweight construction is the combination of different working materials, such as plastics and metals. While plastics are characterized by a nearly infinite number of forming possibilities, a low weight and favorable price, metals can withstand, thanks to their mechanical properties, significantly higher mechanical loads. A direct and firm bond between plastics and metals, however, fails due to the physical and chemical differences between them. Since joining of plastics and metals nowadays is based on adhesive bonding, the joint is weak and underlies ageing processes. A promising approach to overcome these problems is a laser based two-step process [28].

The first process step is the microstructuring of the metal surface by laser radiation. For the surface treatment a scanner based single mode fibre laser system is used to create microstructures with adjustable geometries and orientations. Using this system set up, high processing speeds for efficient production processes can be realized. The following step is a diode laser based joining process. At first both materials are brought into direct contact by external clamping to minimize the gap. The laser beam is focused on the external surface of the metal and by heat conduction the plastic is molten at the interface. For a firm connection, the plasticized material has to flow into the generated structures, which have an undercut geometry, and to harden there.

An application example for this laser based process is a T-Joint connection between micro alloyed steel and a short glass fiber reinforced polyamide. For the diode laser based joining process, a Laserline LDM3000-100 beam source with a wavelength of 1018 nm was used. The beam parameter product of this beam source is **100 mm mrad**. The focusing optic was an adjustable zoom optic, in this particular case the rectangular beam spot was 25 x 4 mm². The joining area was irradiated with a laser power of **800 W** and pulse duration of 1 second. Using this joining parameter leads to a homogeneous filling of microstructures with polymer and glass fibers as shown in Figure 16.

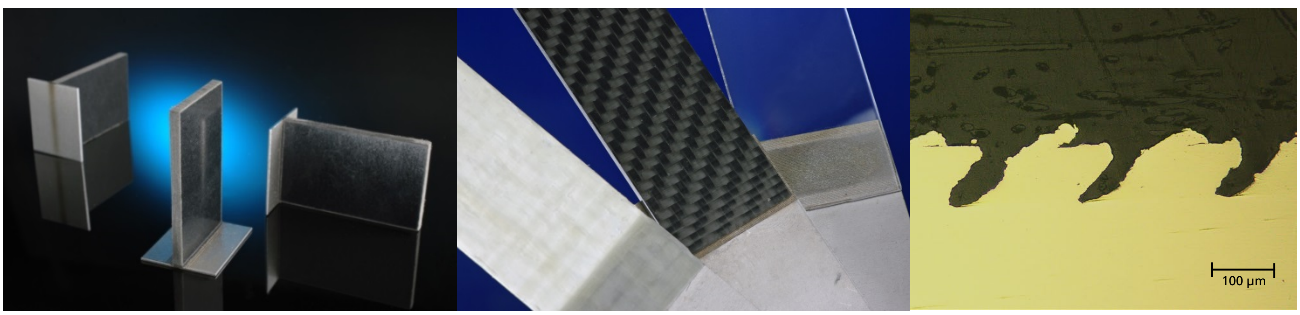

Figure 16: T-Joint (left, materials HC420LA / PAGF30), connection of different plastics and metal material pairings (middle) and cross section of the connection (right).

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6.8 Plastics Welding – Laser transmission welding of absorber-free thermoplastics

Owing to its characteristics, such as temporal and spatial energy deposition, laser transmission welding of thermoplastics has established itself in different branches of industry. Whereas in the past the emphasis was mainly put on weld strength and cycle time nowadays the appearance of the product becomes an important feature. As most thermoplastics are transparent in the spectral range of classic laser sources (800-1100 nm) the absorption of one of the joining partners is usually enhanced by absorbers [29]. The need to add absorbers is considered as the main drawback of laser transmission welding as absorbers not only affect the visual properties of the part but also entail additional costs and process steps. Apart from this, chemical stability and toxicological potential of absorbers might cause issues especially in food contact or medical applications where products underlie strict regulations regarding biocompatibility [30].

To enable laser transmission welding without absorbers the intrinsic absorption of thermoplastics can be exploited by new diode and fiber lasers with emission wavelengths in the mid-infrared range (*Figure 17, left*). For example, diode laser radiation with a wavelength of 1642 nm, an average power of **30 W** and a BPP of about **45 mm mrad** is used for the laser transmission welding process.

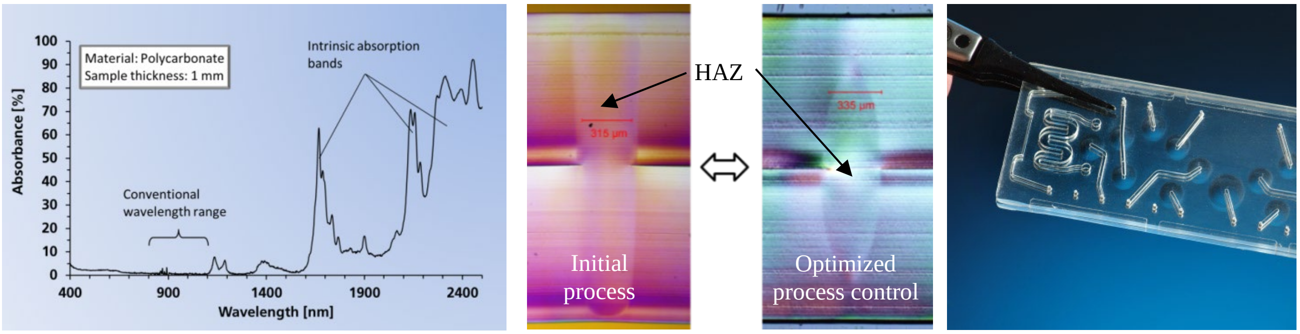

Figure 17: Absorption spectrum of Polycarbonate (left), process control images (middle) and image of a transparent microfluidic component (right, Bartels Mikrotechnik GmbH)

However, without absorbers the incident radiation is evenly absorbed along the beam axis leading to an extensive heat affected zone (HAZ) which represents the area melted during the welding process (*Figure 17, right*). A vertically extended HAZ not only promotes distortion especially for flat components but also indicates a higher thermal stress on the irradiated surface which can cause burning. The main challenge is therefore to fuse the joining partners spatially restricted at their interface. At Fraunhofer ILT different approaches are investigated in order to reduce the vertical size of the HAZ [31]. As presented on the right side of *Figure 17* using appropriate equipment and process control methods a more favorable HAZ shape can be achieved. Thereby, filigree seams can be produced in narrow space which is an important requirement for small scale parts such as micro-fluidic devices.

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6.9 Tempering – production of carbon fibers

Carbon-fiber reinforced plastics (CFRP) are excellent materials for applications in lightweight constructions in the automobile or aviation sectors due to their 2.5 times higher specific strength compared to aluminum. However, the high manufacturing costs of carbon fibers are one of the main limiting factors for the exploration of new fields of applications. The precursor fibers mostly consist of polyacrylonitrile (PAN) which is transformed into carbon fibers in furnace processes.

A new laser-based manufacturing process for carbon fibers has been developed at the Fraunhofer ILT and shows potential for the implementation of a fabrication process with reduced energy and time costs compared to the conventional furnace based approach. Furthermore, the excellent adjustability of the spatial and temporal energy deposition via laser allows an adaptive process control which has the potential to fabricate fibers with increased mechanical properties in shorter times.

The experimental setup consists of a winding machine, two optics for beam shaping and an assembly of an inner and an outer process chamber where the heat treatment of the fibers (*Figure 18*) takes place. A diode laser with wavelengths of 968 nm and 998 nm, a beam parameter product of **30 mm mrad** and a maximum laser power of **800 W** is applied. The laser is equipped with a beam splitter which divides the laser power on two optical fibers to process the carbon fibers at two locations in parallel. This setup reduces the number of times the fiber has to be moved under the laser beam.

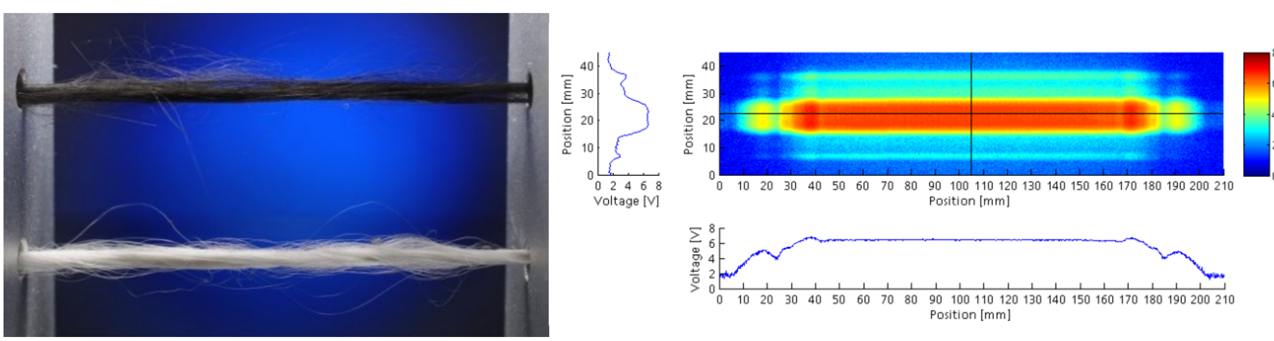

Figure 18: PAN fibers and black carbon fibers (left), measurement of the intensity profile (measured as voltage, arbitrary units) of a laser spot with a dimension of 150 x 10 mm² and a laser power of 640 W (right).

The modular design of the optics allows for generating laser spots with a width of approximately 10 mm and a length of approximately 100 mm or 150 mm (*Figure 18*). For the measurement of the laser intensity profile with these rather large dimensions a measurement device was developed in-house at the Fraunhofer ILT.

The laser intensity is rather homogenously distributed in an area of approximately 130 x 10 mm (*Figure 18*). Above and below this “homogenous area” smaller side lopes with locally increased laser intensity are detected, which is typical for homogenization optics based on micro-lens arrays. Again fiber-coupled edge-emitter based diode laser sources are used in combination with a homogenizer. In this case, the working distance determines the beam quality.

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6.10 Sintering & tailored heating

The sintering of metallization lines on solar cells is a typical example for NIR digital heating solutions that can be performed with high-power VCSEL arrays. In a joint project, Rehm Thermal Systems and Philips Photonics have integrated a **9.6 kW VCSEL** module with about **10^4 mm mrad** in a commercial fast firing line [32]. The aim of the project is to improve process control and product quality. Furthermore, the VCSELs enable new compact machine concepts. 400 test wafers have been processed by now. An “ultrafast temperature rise” of 1050 K/s has been confirmed experimentally using the VCSELs [33]. Tests have been performed with an output power of up to 4.8 kW at a feeding speed of 5 m/min. In comparison, the classical heating system is restricted to 130 K/s [33]. Furthermore, control and speed are superior to conventional heating methods. Compared to a solution based on edge-emitters, the cost of the VCSEL system is lower by a factor between 2 and 5 [33]. The principle can be used in other thick-film processes e.g. passive electronic circuits and printed electronics.

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6.11 Carbon fiber placement

With typical intensities of **100 W cm^{-2}** the power density of VCSEL arrays is sufficient to melt plastics or to treat thermally melting glues at high process speed. Moreover, to produce composite materials heat is required at the tape laying head while placing the carbon fibers on a substrate. Simulation results from Philips Photonics have been published to demonstrate the feasibility of a 30 m/min carbon fiber placement with a **400 W cm^{-1}** NIR rectangular heat profile. Processing a 6 mm wide and 0.2 mm thick carbon fiber tape, the process temperature of 300 °C is reached within 0.1 s which is more than sufficient for a stable process.The experimental results confirm the simulation. The output power of the VCSEL-array is **1.6 kW**. The BPP is in the order of **10^3 mm mrad.**

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7. PROCESS REGIMES

The modulation of laser radiation in time, space and frequency over several orders of magnitude enables the adaption of the beam source to the demands of process technology. Beside the wavelength, the most important characteristics for cw applications are the beam parameter product and the optical power (*Figure 19*).

To increase the power, spatial multiplexing is a common technology. By arranging edge-emitters or VCSELs in arrays, stacks and modules, the output power increases, but at best, the radiance B (brightness) stays constant (green lines in *Figure 19*).

$$B = \frac{P}{A_T \Omega} = \frac{P}{\pi^2 BPP_x BPP_y}$$

(P: optical output power, A_T: area of the beam waist, Ω: solid angle)

One possibility to increase the brightness is the use of laser sources with shorter wavelengths and a further development of the beam sources. Besides, coarse wavelength division multiplexing and dense wavelength multiplexing technologies have been implemented in industrial products during the last years. While the BPP stays almost constant, the power and therefore the radiance increase at the cost of spectral radiance (spectral brightness) (*Figure 19*).

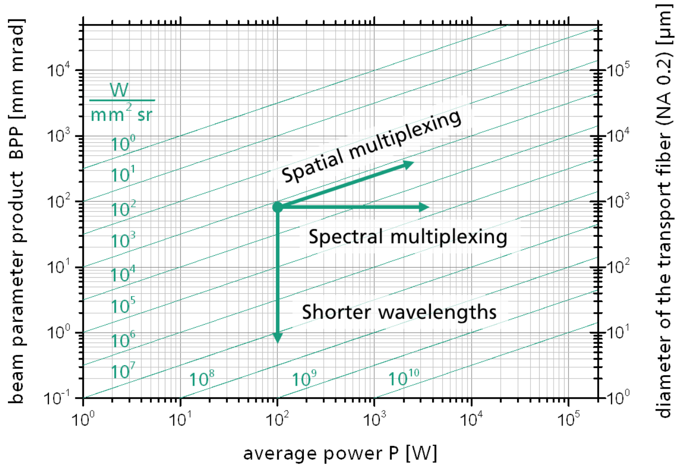


Figure 19: Power scaling concepts and their influence on the brightness of laser systems. [1]

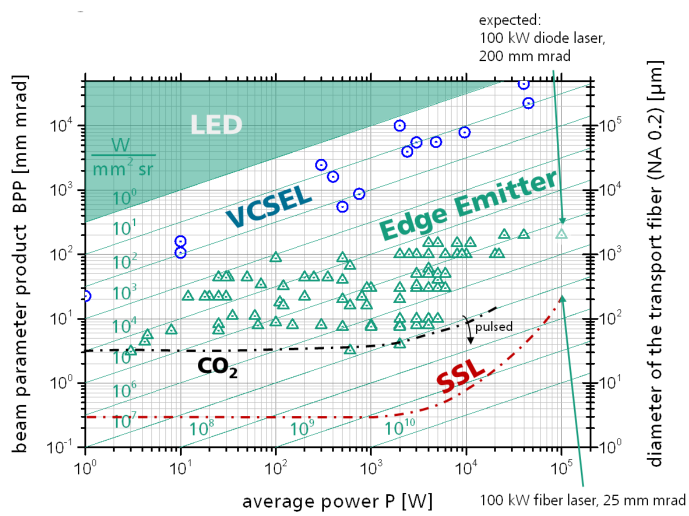
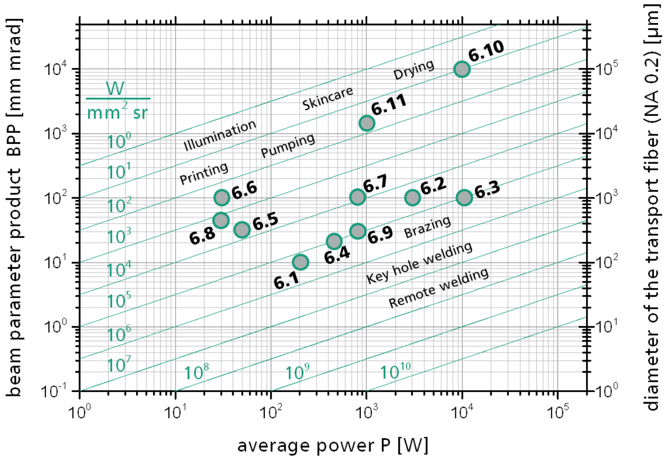


Figure 20: Brightness, beam parameter product and power of industrial laser systems. [1]



sec.	application	power	BPP
6.1	SLM	200 W	10 mm mrad
6.2	LMD	3000 W	100 mm mrad
6.3	Laser treated steel	12000 W	100 mm mrad
6.4	Soldering, photovoltaics	500 W	20 mm mrad
6.5	Soft Soldering	50 W	30 mm mrad
6.6	VCSEL Illumination	32 W	100 mm mrad
6.7	Plastics welding - hybrid connection	800 W	100 mm mrad
6.8	Plastics welding	30 W	45 mm mrad
6.9	Tempering	800 W	30 mm mrad
6.10	Sintering & tailored heating	9600 W	10^4 mm mrad
6.11	Carbon fiber placement	1600 W	10^3 mm mrad

Figure 21: Brightness, beam parameter product and power of industrial laser applications for diode lasers. The applications are explained in the corresponding sections 6.1 – 6.11. Furthermore, some additional process regimes are labelled.

It is well known that the different types of beam sources cover specific areas of brightness. The new high-power VCSELs (*Figure 20*, round symbols) cover the area of $10^0 – 10^3$ W mm^{-2} sr^{-1} and are therefore arranged between LEDs and high-power diode laser systems based on edge emitters (EE). By improving the diode laser systems based on EEs and especially by implementing spectral multiplexing technologies, the radiance has reached the area between 10^6 and 10^7 W mm^{-2}sr^{-1} (*Figure 20*, triangle symbols). Therefore, in the last years CO_2 and rod lasers (for cw operation) have been substituted by diode laser systems based on edge-emitters. Currently, the area of $B > 10^7$ W mm^{-2} sr^{-1} remains reserved to solid state laser systems (*Figure 20*, SSL). In May 2014 (AKL 2014, May. 6.-9) Laserline has presented a measured P-I characteristic of a direct-diode laser system with 40 kW output and 200 mm mrad. The system bases on standard building blocks which is characteristic for high-power diode laser systems and can be upgraded to 48 multi-stack modules operating at 8 different wavelengths (*Figure 20*, arrow). Completely equipped, the maximum configuration will have >100 kW of output power and a beam quality of 200 mm mrad. Therefore, it will only be a matter of time until direct diode laser systems reach powers of 10^5 W.

To calculate the required radiance for various applications, many requirements have to be taken into consideration. E.g. the required radiance for plastics welding is determined by the absorption and the material combinations. As a further example, the radiance for remote welding – which is a very sophisticated application – strongly depends on the working distance and the required welding speed. Therefore, the process map (*Figure 21*) indicates the laser applications in a very rough approximation.

Edge-emitters have been used in heating applications and especially for surface treatment like hardening since they are available at sufficient power and reliability [34]. The inhomogeneous beam characteristic states a major drawback of these devices: the multimode lateral intensity profile is undefined on the facet surface as well as in angular space. Although the vertical eigenmode is well defined, it is not homogeneous either. In addition, single emitters and bars can fail during their lifetime. To overcome these problems, the intensity distribution is homogenized either by a waveguide or by microoptic devices [35].

Because of their rotationally symmetric circular far-field (without optics) and the near-field top-hat intensity distribution, VCSEL based laser systems do not require complex optics for homogenization. Using a simple imaging optics including a micro-lens array, an almost arbitrary number of VCSEL nearfield intensities can be overlaid to a very homogeneous image. Electrically-controllable beam profiles can also be realized [36].

These properties fit the requirements of several high power applications which are not restricted to a high beam quality. In the region of $B < 10^2$ W mm^{-2} sr^{-1} especially drying, skin care and homogeneous illumination benefit from the development of high-power VCSELs (*Figure 21*). Experiments in which VCSELs operate as a pump source are of course limited to laser-active materials which do not require high brightness for efficient lasing. For cw-pumping of Yb:YAG which has a quasi-three-level behaviour, currently only edge-emitters show the required brightness. Nevertheless, there are benefits for transversal pumping of Nd:YAG rod lasers or qcw-pumping of Yb:YAG by VCSELs. The typical pump wavelength of 808 nm is available and the thermally induced spectral shift is comparable small (0.06 nm/K). Furthermore, very compact integrated designs can be developed.

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8. SUMMARY AND CONCULSION

In addition to the high-brightness applications, edge-emitters with comparatively low demands concerning the radiance ($< 10^2$ W mm^{-2} sr^{-1}) have been used in the fields of NIR heating and drying. However, the brightness of diode laser systems based on edge-emitters has been improved continuously over the last ten years, extending the range of applications that can be addressed. Nowadays, radiances up to 10^7 W mm^{-2} sr^{-1} have been demonstrated.

The new high-power VCSEL arrays address the brightness regime $< 10^3$ W mm^{-2} sr^{-1} between lamps, LEDs and edge-emitters. Especially the comparatively cheap package and mounting and the homogeneous intensity distribution without expensive optics are major advantages. The major part of classical laser applications is still restricted to edge-emitter based laser systems, but heat treatment like hardening of thin steel sheets and surface modifications can be performed by cheaper VCSEL systems.

In conclusion, power scaling by wavelength multiplexing and increased efficiency will result in further records in the field of diode laser based beam sources – either based on VCSELs or on edge-emitters. For sophisticated applications which require high brightness and a low BPP at the same time solid state lasers like fiber and disk lasers are still most convenient. At the moment, there are many research projects which focus on the enhancement of the brightness of diode laser systems by dense wavelength division multiplexing and coherent combining. Future high-brightness beam sources can only prove themselves on the market if the price, the efficiency and the stability will be comparable to state-of-the-art solid state laser systems.

As shown in sec. 6 there are many applications which require a medium brightness of $10^1 – 10^5$ W mm^{-2} sr^{-1} . In addition the number of produced high-brightness diode laser pumping modules – which are not discussed in this paper – will increase. In sum, there are good prospects for the growth of the diode laser market share.

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A shortened version of this paper has been prepublished in [1].

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