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1.1 Executive summary

The BRIDLE project sought to deliver a technological breakthrough in cost effective, high-brilliance diode lasers for industrial applications. Advantages of diode lasers include highest efficiency for transforming electrical energy into laser radiation (up to 70%), compact and long-term stable systems, and the availability of various wavelengths from UV to SWIR. On the downside, commercially available direct diode laser systems suffer from a significantly lower brightness compared to high power NIR laser systems based on additional active media like fiber lasers, disc lasers and slab lasers. Due to this limit, diode lasers are well established for applications which demand only low brightness like pumping, polymer welding and brazing, while high-quality sheet metal cutting with diode lasers was not available at the beginning of the project. Consequently the main objective of the BRIDLE project was the scaling of the diode laser's brightness. A well-balanced consortium of 7 leading industrial, research and academic partners followed three routes in parallel to reach a significant increase of the brightness by scaling the output power while maintaining the beam parameter product: the first approach was based on coarse wavelength division multiplexing of high-brightness diode laser modules. For the second one, dense wavelength division multiplexing of internally and externally stabilized diode laser bars was used, and the third approach sought to scale the output power by coherently coupling single diode laser devices. As the final goal, a high power demonstrator system based on one of these technologies has been be set up and used to demonstrate sheet-metal cutting with the developed direct diode laser system.

According to this the work in the BRIDLE project was structured in the following work packages:

- Develop of the semiconductor laser technology needed for the realization of novel high performance high-brilliance direct diode laser systems. Initial prototypes of three main diode laser designs were produced for an initial performance assessment and the construction of prototype sub-modules, including tapered laser and narrow-stripe-BA laser mini-arrays for dense spectral beam combined sub-modules and single mode laser arrays for coherent beam combined sub-modules. (WP 2)
- Design as well as theoretical and experimental analysis of the optics needed for the multi-kW prototype based on dense wavelength division multiplexing. The optics design of seven spectral beam stabilization technologies has been compared. (WP 3)
- Coherent beam combining (CBC) of high-brightness lasers for increasing the brightness of diode laser arrays while maintaining a narrow linewidth, including the evaluation of different external-cavity architectures for the passive phase-locking of lasers. (WP 4)
- Optimizing designs for emitters and mini-bars suited for spectral beam combining and coherent beam combining, respectively. This includes also the calibration and expansion of the existing software tools. (WP 5)
- Finalizing the design of the subsystem architecture and development of the design of the multi-kW laser system. The architecture was based on small building blocks, including the dense spectral beam combination technology. Fibre combiners and coarse spectral beam combining technologies has then been used for power scaling to the multi-kW power range. (WP 6)
- Evaluation of the developed diode laser modules and systems, including the characterization of the laser beam (output power, beam quality, power stability etc.) and the wall-plug-efficiency of the laser module / system as a whole. The applicability of the laser source for the 2D sheet metal macro cutting application has been demonstrated, including the integration of the laser into the cutting machine. (WP 7)

Due to the complexity of the BRIDLE project, an additional work package was implemented for the project management (WP 1). Finally, dissemination and exploitation activities were bundled together in WP 8.

Key achievements

Work Package Topic (Main partner)	**Description**	**Achieved Results**
Bar Fabrication (FBH)	High brilliant NBA mini-bars for incoherent beam combining and coarse spectral multiplexing	7W per emitter @ 1,5 mm-mrad, efficiency >50% at 910, 940 and 970nm
Bar Fabrication (FBH)	Internally grating stabilized DFB-NBA mini-bars for dense spectral multiplexing	5W per emitter @ < 2 mm-mrad, 50% efficiency, 2,5nm wavelength spacing on a bar
Bar Fabrication (Modulight)	Design platform for RWG (Ridge Waveguide) Lasers at 975nm for coherent combining experiments	1W output power from 4µm single emitter, efficiency >35%, new facet coating technology
Spectrally Beam Combination (ILT)	Optics design and development, Ultra-steep dielectric filters, comparison of power scaling schemes	52% optical to optical efficiency with DFB mini-bars, 46W @ 35µm fiber **(Bridle S5)**
Coherent Beam Combining (CNRS)	Investigation of new CBC architectures, demonstration with two emitters and scaling to mini-bars	Up to 7,5W in a single beam, M^2<1,3, combing efficiency up to 92%, 11,2W combined power with 76% combining efficiency with active stabilization **(Bridle-C1)**
External cavity laser simulation (UNott)	Development of a self-consistent quasi-3D dynamic laser simulation tool, coupling with external cavity simulation tool and raytracing software	Successfully implemented different design iterations in tapered lasers, RWG lasers
High power, high brightness laser modules (Dilas)	Sub-modules in commercial housing, wavelength stabilized to three densely spaced wavelengths (2,5nm spacing) and two coarse wavelengths (940 and 975nm)	6W per 50µm diode emitter, 320W from 100µm fiber within NA 0.15, e.-o. efficiency 45% **(Bridle I1)**
High power, high brightness laser modules, combined system (Dilas & ILT)	Final Bridle System realized and used successfully for cutting application and Selective Laser Melting (SLM)	800W from a 100µm fiber, NA 0.15 More details: www.bridle.eu

1.2 Summary description of project context and objectives

BRIDLE (Brilliant Industrial Diode Laser) targeted a major increase in the achievable brightness in direct diode laser systems, based on advances in diode laser and beam-combining technology. At the beginning of the BRIDLE project, high power diode laser systems in the multi-kw regime were commercially available, but these systems were not suited for applications which demand high brightness like sheet metal cutting (see Fig. 1). Typical fiber core diameters of high-power diode laser systems were ≥ 600 µm, and main markets for direct diode lasers were pumping of solid state lasers, transformation hardening, brazing and polymer welding.

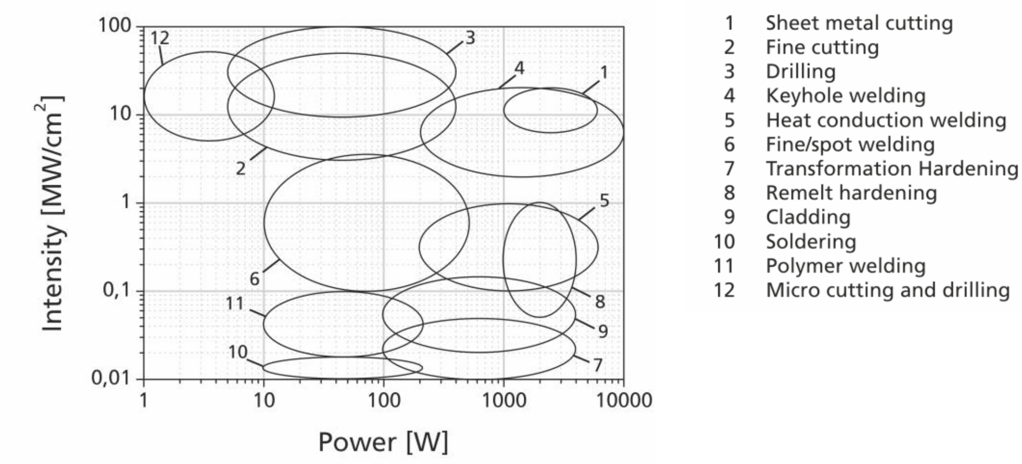


Fig. 1: Typical power and intensity requirements of high power laser applications.

To scale the output power of high power diode laser systems, the following techniques were implemented in 2012:

- Spatial multiplexing as a simple concept for power scaling,

- Polarization multiplexing, and

- Coarse wavelength division multiplexing.

While the first concept allows only power scaling but no brightness scaling, the latter two concepts are limited to a factor of two (polarization multiplexing) and three to eight (coarse wavelength multiplexing) in terms of brightness scaling. Limiting factors for wavelength multiplexing were the availability of steep edge filters and the number of wavelengths available. With an achieved intensity exceeding 10 MW/cm² (NA 0.17), the final BRIDLE demonstrator was successfully used for sheet metal cutting, thus broadening the range of direct diode laser applications towards domains which are dominated by CO_2-, fiber and disc lasers.

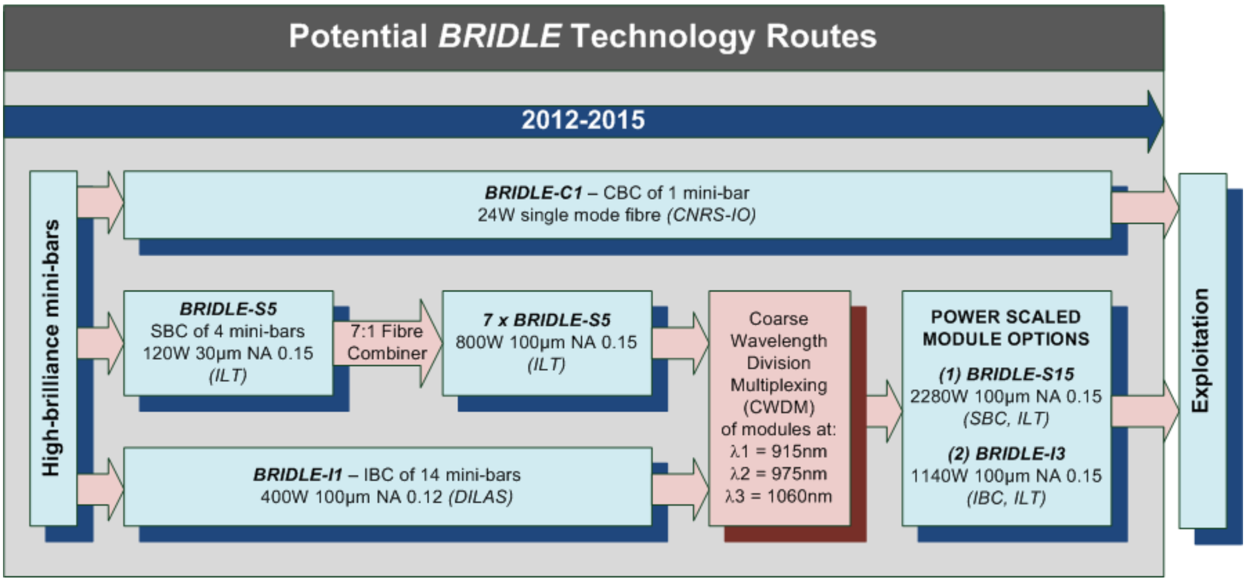


Fig. 2: BRIDLE's initial technology development approach.

As shown in Fig. 2, various innovative technologies were investigated within BRIDLE to overcome the limitations of conventional high power diode laser systems. The consortium focused on the improvement of the brightness of the diode laser chip, the development of efficient coarse division and dense division multiplexing schemes as well as coherent beam combining of high power laser diodes.

Design and technological development of high performance diode lasers was performed by three partners. The **Ferdinand-Braun-Institut, Leibniz-Institut für Höchstfrequenztechnik ("FBH")** developed novel epitaxial designs and process technology. Those developments enabled the use of broad area mini bars with a narrow stripe width of only 30 µm to operate with a brightness that is increased by at least a factor of two in comparison with state of the art chips with a 100 µm stripe width. Furthermore, highly brilliant narrow-stripe DFB diode lasers with monolithically-integrated surface gratings were developed and optimized which are suited for dense wavelength division multiplexing. These devices deliver simultaneously narrow spectrum (< 1nm), high power (5W), high efficiency (50%) within a low beam parameter product (< 2mm-mrad) for the first time. For coherent coupling experiments, monolithically grating-stabilized tapered diode lasers were developed, with record (54%) conversion efficiency. Second, ridge waveguide diode lasers for coherent coupling experiments were developed by **Modulight Inc. ("Modulight"),** which deliver an output power of 1 W per emitter. Finally, design optimization was supported through detailed simulation work performed by **University of Nottingham ("UNott")**.

Based on the high brightness diode laser mini bars developed within the BRIDLE project, **DILAS Diodenlaser GmbH ("DILAS")** was able to simplify and expand its well-known T-bar concept for 105 µm fibre coupling. Furthermore DILAS could increase the optical output power up to 300 W ex 100 µm. The emission wavelength can be stabilized. Thus the modules were also used for dense wavelength division multiplexing to further increase output power and brightness. The assembly process of the modules is fully automated, enabling cost-efficient mass production of high power diode laser modules.

Fraunhofer Institute for Laser Technology ILT ("ILT") analyzed and compared different techniques for dense wavelength multiplexing. These techniques include different approaches based on surface gratings, simultaneous wavelength stabilization and multiplexing by use of dielectric filters and VBGs as well as DWDM of wavelength chirped DFB diode lasers by dielectric filters. Filters from different international manufacturers were tested thoroughly. For the first time, Fraunhofer ILT has developed concepts which can be used to implement and test compact modules in the medium power range of 10 W to 100 W output power, with a fiber having a core diameter of 35 µm and a numerical aperture of 0.2. 46 W were realized experimentally. A 7:1 fiber combiner (35/105 µm) was developed for further power scaling.

Centre National de la Recherche Scientifique/Institut d'Optique ("CNRS-IO") demonstrated a new architecture for passive coherent combining of diode laser with ridge lasers (delivered by Modulight) and tapered lasers (delivered by FBH). The set-up is based on the separation of the phase-locking stage, which takes place in an external cavity on the rear side of the lasers, and the beam combining stage, which is achieved outside the cavity on their front side. This configuration demonstrates successively a combined power up to 7.5 W in a single beam from a bar of five high-brightness emitters, using a specifically designed diffractive combiner. Furthermore, the active coherent combining of five tapered amplifiers achieved a power of more than 11 W with a combining efficiency of 76%.

The **University of Nottingham** developed software tools that enable the investigation of coupling between external optics and the diode laser itself. These tools can be used to better understand coherent coupling, wavelength stabilization or parasitic back reflections. UNott developed a dynamic laser simulation tool for CBC diode laser systems. This tool is used in conjunction with external cavity models developed at CNRS-IO to investigate the nature and dynamics of the phase locking mechanisms in CBC laser systems. Furthermore, UNott's laser simulation tool Speclase was coupled to external optical design software (ZEMAX®) for external cavity simulations at the subsystem level.

Industrial applications of the developed prototypes are investigated by **Bystronic Laser AG ("Bystronic")** and **Fraunhofer ILT**. Lasers manufactured by DILAS have been used for Selective Laser Melting of metals at Fraunhofer ILT, and Fraunhofer ILT demonstrated sheet metal cutting with the high power diode laser system developed and set up within the BRIDLE project.

When the BRIDLE project was planned, the main application targeted by the consortium was sheet metal cutting as an innovative application of direct diode laser systems. In the course of the project, it became obvious that Selective Laser Melting specifically benefits from compact, low cost and high brightness diode laser sources. Consequently, Selective Laser Melting was added as a second demonstration application.

The BRIDLE project helped to increase significantly the technology readiness level (TRL) of several high power diode laser technologies. The TRL allows to estimate the maturity of a technology, going from 1 if basic principles are observed to 9 if the actual system is proven in operational environment. The following table summarizes the achieved TRL of different innovative technologies investigated in BRIDLE:

Technology	**Achievement**	**TRL before BRIDLE**	**TRL at the end of BRIDLE**
High power, high lateral brightness diode laser bars, internally stabilized	Mini bars with chirped grating manufactured and tested in lab environment, mini-bars were successfully integrated into fibre coupled prototypes	1	5
High power, high lateral brightness	Brightness doubled compared to the state-of-the-art, demonstrated in	4	6

diode laser bars	relevant environment		
Package for individually addressable emitters with rear and front facet access	Package for diode laser bars with individually addressable emitters (and sections in case of TPLs) for both rear and front facet access manufactured and tested in lab environment	1	3
Coherent combining of high power diode laser bars	5 emitter tapered DL bars and 10 emitter RW laser bars passively phase-locked by means of an extended rear-side cavity	1	4
Coherent combining of high power diode laser bars	5-emitter tapered DL bar actively phase-locked and coherently combined into a single beam with power >10 W in a MOPA configuration.	2	4
Design of diffractive combiner	Design & evaluation of high efficiency diffractive optical elements for the coherent combining of laser beams	2	3
Individually-addressable current controller	Independent control of the currents in an array of 10 emitters using a single current driver	1	2
High brightness 7:1 fiber combiner	35 µm NA 0.12 to 105 µm NA 0.15 combiner manufactured and tested in lab environment	1	3
High brightness fiber coupled diode laser module	35 µm module based on dense wavelength division multiplexing set up and tested in lab environment	1	4
High power diode laser system for sheet metal cutting	Demonstrator based on 6 wavelengths set up and tested in relevant environment	1	6

1.3 Description of the main scientific and technological results / foreground

1.3.1 Bar fabrication

In WP2, in work at the FBH, highly brilliant diode laser minibars have been successfully developed, fabricated and delivered to BRIDLE project partners to enable the construction of cost-efficient, high performance diode laser modules for direct material processing applications. These diode lasers offer substantially higher performance than state of the art commercial devices.

First, advanced epitaxial designs and process technology enabled novel narrow-stripe broad-area lasers (NBA lasers) to deliver 7 W output power per emitter within a beam parameter product of *BPP* = 1.5 mm-mrad, corresponding to a brightness double that of commercial devices, with a conversion efficiency (50…55%) compatible with industrial application. Results are shown in Fig. 1 for exemplary single emitters, which were fabricated and delivered at three different widely space wavelengths (Lambda = 910 nm, 940 nm, and 975 nm), to enable power scaling in direct diode laser systems via incoherent beam combining and coarse spectral beam combining.

Second, design and process technology was developed to enable the fabrication of NBA laser minibars where each emitter operates at a different wavelength, stabilized using a monolithically-integrated surface grating. These DFB-NBA lasers delivered 5 W per emitter output power at *BPP* = 1.8 mm-mrad with 50% conversion efficiency, with an emitter-to-emitter wavelength spacing of 2.5 nm, as shown in Fig. 3. Such DFB-NBA laser mini-arrays enable power scaling via dense wavelength beam combining in compact, cost-efficient direct diode laser modules. These results have been publically shared via technical papers and conference presentations, and technology protected via patent application.

In addition, additional diode laser minibars have been successfully developed, fabricated and delivered, that are customized for use in studies into coherent combining of diode lasers. This includes the development and delivery of tapered lasers at the FBH and ridge waveguide lasers at Modulight.

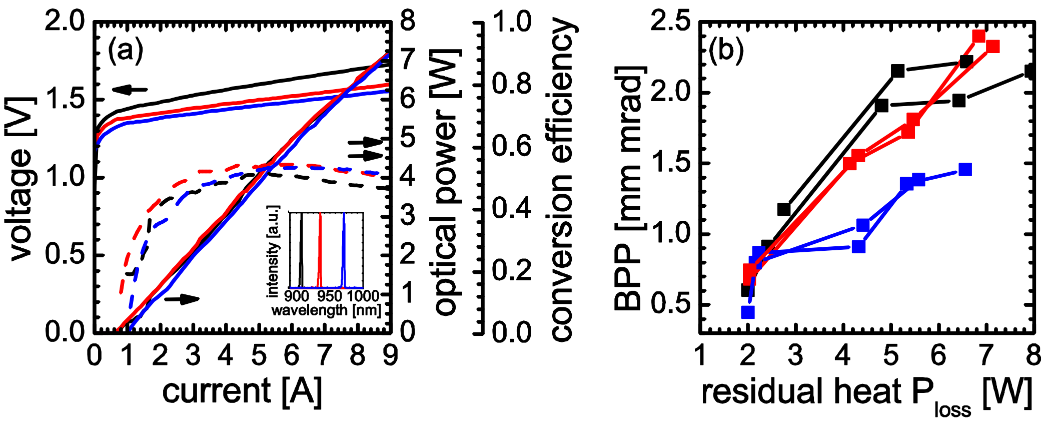


Fig. 3: Performance of gain guided NBA lasers lasing at 910 nm (black), 940 nm (red) & 975 nm (black). (a) Voltage, power and power conversion versus current (b) Beam parameter product as a function of residual heat (P_{loss} = P-VI).

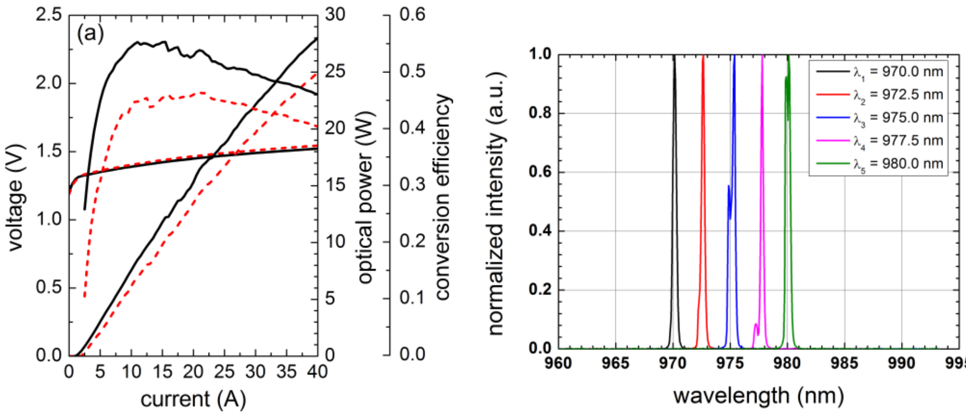


Fig. 4: Performance of DFB stabilized minibars (20°C, continuous wave), inferred from single emitter data. (Left) Voltage, power and efficiency for final BRIDLE bar configuration (solid) compared to previously delivered reference material (dashed). (Right) Normalized spectrum at 5 W per emitter.

Modulight has developed ridge waveguide (RWG) laser devices and related manufacturing techniques at 975 nm wavelength. The design concept developed within the project is found out to be suitable for high-power RWG devices up to 1 W power and is expected to be suitable for a wider wavelength coverage. Specific design versions of RWG lasers and arrays were used in coherent beam combining (CBC) experiments within the BRIDLE project.

Modulight's role in the BRIDLE project was to develop high-power RWG laser devices at 975 nm wavelength. The RWG devices were specifically targeted for CBC experiments conducted within the BRIDLE project. The RWG laser device development was divided into 2 milestones with the targets set based on the output power. Modulight's project deliverables consisted of 2 sets of RWG devices specifically tailored for the CBC experiments with additional design optimisation work in between based on the feedback obtained from the first deliverable devices. The CBC application sets specific requirements for the vertical design, device layout and facet coatings and these requirements were taken into account during the development work.

The RWG device development was carried out in co-operation between the project partners. The designing and optimisation of the RWG devices was done by University of Nottingham. Modulight provided material inputs, manufactured the devices based on the designs recommendations and provided feedback and results from the device iterations and variants for further optimisation work.

The initial requirements for the CBC were set by CNRS-IO, where the actual CBC experiments were also conducted. The device array layout for the CBC experiments was tailored together with ILT and CNRS-IO as ILT was handling the wiring and packaging of the arrays. The manufacturing process was realized and the arrays were prepared by Modulight.

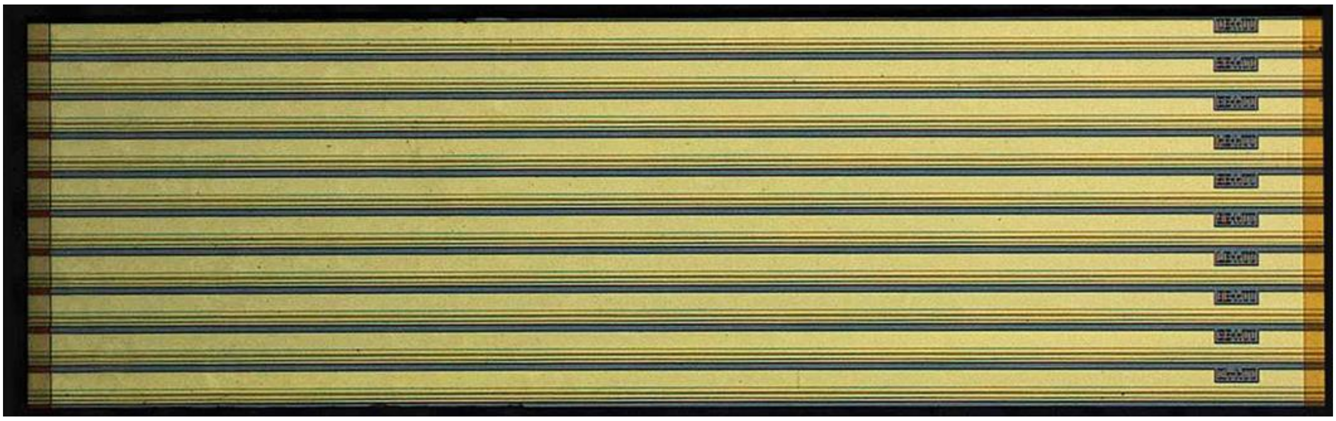


Fig. 5 Ridge waveguide (RWG) laser array with 10 individually addressable emitters manufactured by Modulight in BRIDLE project. The emitters and the array have been designed for coherent beam combining (CBC) application and include a specific facet coating. The same design platform has been found to be suitable for preparing RWG laser devices up to 1 W output power at 975 nm and surrounding wavelengths.

The RWG development consisted of 2 vertical design iterations each including multiple design variants. In between the iterations optimisation of the design was performed based on the results obtained for the first iteration devices.

As a result of the project efforts a new generic design platform for RWG lasers at 975 nm and surrounding wavelengths was developed. The design platform has been shown to be suitable for manufacturing RWG devices up to 1 W output power. To fully exploit commercially the potential of the design platform in CBC and also in a wider range of applications some additional optimization is needed. The improved manufacturing techniques including facet coating designs and mesa etching process developed during the project provide a solid basis for the work.

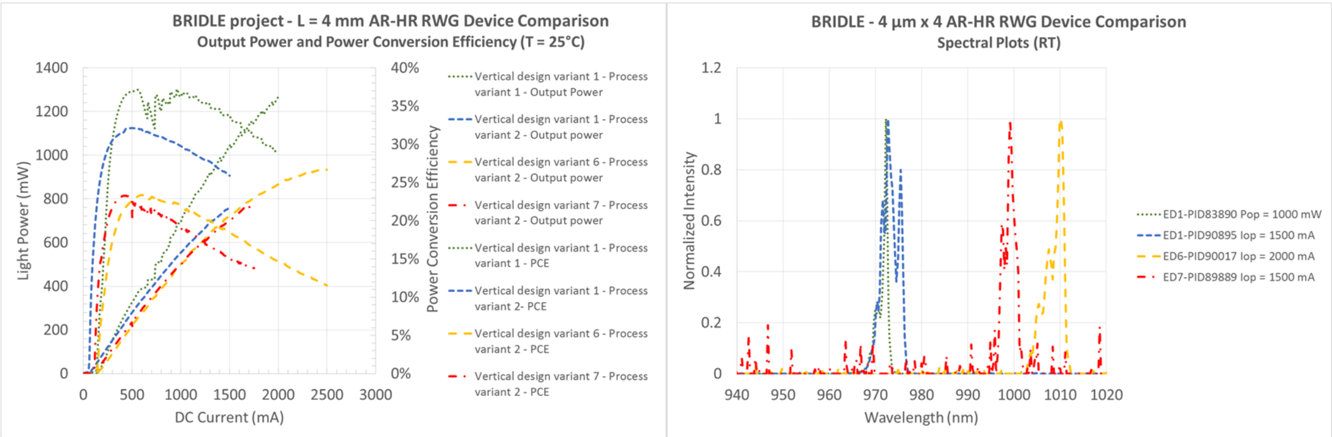


Fig.6 Results for different design variants of AR-HR coated RWG devices developed within the BRIDLE project. The highest output exceeds 1 W output power and shows the potential and capability of the design platform developed in project.

In addition to the CBC application, Modulight sees that the RWG laser development performed with BRIDLE project offers others potential exploitation possibilities. One interesting application is Raman Spectroscopy for which stable high-power single mode lasers at 785 nm, 830 nm, 980 nm and 1064 nm wavelengths are used. The RWG laser design concept developed within BRIDLE project is expected to be suitable also for the surrounding wavelengths of 980 nm and therefore provide a basis to cover all the listed wavelengths. The manufactured laser chips based on the design concept or platform can be incorporated into laser sub-systems and system products offered by Modulight and this improves the possibilities to address a wider customer base requiring different form of the devices.

The improvements in the manufacturing techniques and particularly the new facet coating designs concepts developed within BRIDLE project are transferrable for the other type of devices such as superluminescent diodes (SLD's), gain elements and semiconductor optical amplifiers (SOA's) in a wider wavelength range. Modulight has seen increasing interest in the market for such devices and has exploited already the design concepts for some of these devices at different wavelengths.

Bar packaging

During the project, DILAS was responsible for the mounting of the different types of laser bars developed by the partners as well as from commercial suppliers for the high power module build-up. For qualification purposes, electro-optical characterisation and testing, bars from the partners were mounted on standardised passively cooled heat-sinks.
Progress was achieved in adapting soldering processes to the specialised high brightness bars made by FBH, reducing mounting induced strain which may lead to reduced degree of polarisation and improving cooling performance by a reduced thermal resistance.
For the high power modules used in the final demonstrators, commercial type mounting processes are applied. Laser bars designed specially to meet the beam quality needed in Bridle have been soldered to ceramic sub-mounts and to tap-water cooled copper base-plates. All final systems have been delivered to the partners within adapted commercial housings.

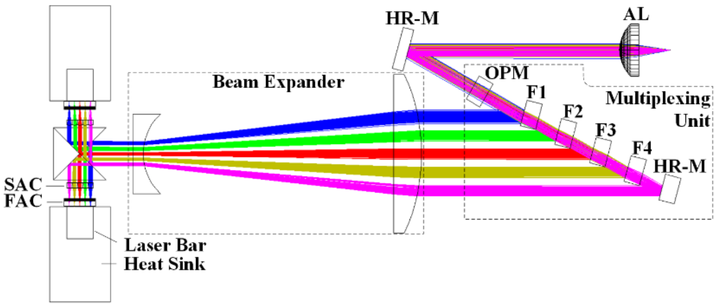
1.3.2 Spectrally beam combined emitters and bars

In WP3, the optics for the high power high brightness diode laser modules with 35 µm fibres were designed by theoretical and experimental analysis. The optics design of seven technologies for chirped wavelength stabilization of high power diode laser bars were compared: (1) transversally chirped VBGs, (2) distinct VBGs, (3) Littrow set-up, (4) internally stabilized DFB-diode lasers (developed in WP2 by FBH), simultaneous wavelength stabilization and multiplexing based on (5) surface gratings, (6) VBGs and (7) ultra-steep dielectric filters.
In addition, this work package focussed on the development of highly-efficient spectral beam combining technology. Different approaches based on dielectric filters, surface and volume gratings were compared with regard to efficiency, angular and spectral selectivity and specific costs.

The ultra-high-brightness fibre coupling into a fibre with a very small core diameter (d = 35 µm) sets the highest standards for the calculation of the fibre coupling efficiency, losses and the thermal management as well as mechanical tolerances. A stacking and multiplexing scheme for the spectrally beam combined mini-arrays with 5 emitters was developed.

Optics design

For the demonstrator module, a modular and flexible set-up was chosen to investigate dense wavelength division multiplexing of internally and externally stabilised diode laser bars. First, the laser radiation is collimated by a fast axis collimating lens, and two diode laser bars are geometrically stacked in the fast axis direction by a pair of reflective prisms. The slow axis is expanded by a telescope to reduce the slow axis divergence (i.e. equalize the divergence of the slow and fast axis) and allow spectral combining by ultra-steep dielectric mirrors. If the set-up shall be used for external stabilisation, a suited output mirror (OPM) can be added to the setup. Fig. 7 left shows a top view sketch of the setup suited for external stabilization, and on the right hand side, the first prototype is shown. To improve the mechanical and thermal stability, all components are precision mounted on one common copper baseplate.



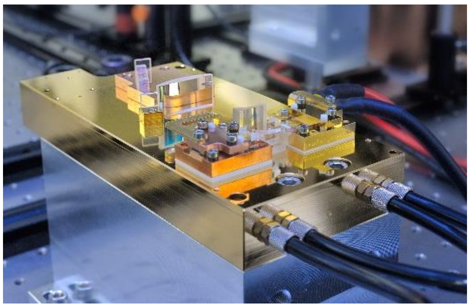


Fig. 7 Optics design for 2 externally stabilized NBA mini bars including DWDM and optical stacking (left). First prototype consisting of 2 actively cooled DFB mini-bars that are optically stacked in the FA (right).

Characterisation of the ultra-steep dielectric filters

The ultra-steep dielectric filters used for this work were characterized at the Fraunhofer ILT. The characterization platform consists of wavelength tunable diode laser used to measure both the transmittance and the reflectance as a function of the wavelength. Furthermore, the transmittance is measured as a function of the angle of incidence by rotating the filter in a piezo driven manipulation stage. The wavelength is measured with an accuracy of 0.02 nm and the AOI with an accuracy of 0.01°. This characterization platform enables both to measure the homogeneity of reflectance and transmittance as a function of the filter position and the influence of the absorption of laser radiation. As can be seen in fig. 8, the filter design chosen for BRIDLE is well suited for dense wavelength division multiplexing with a spacing of 2.5 nm (right), and the filters can be manufactured with a very good reproducibility (left).

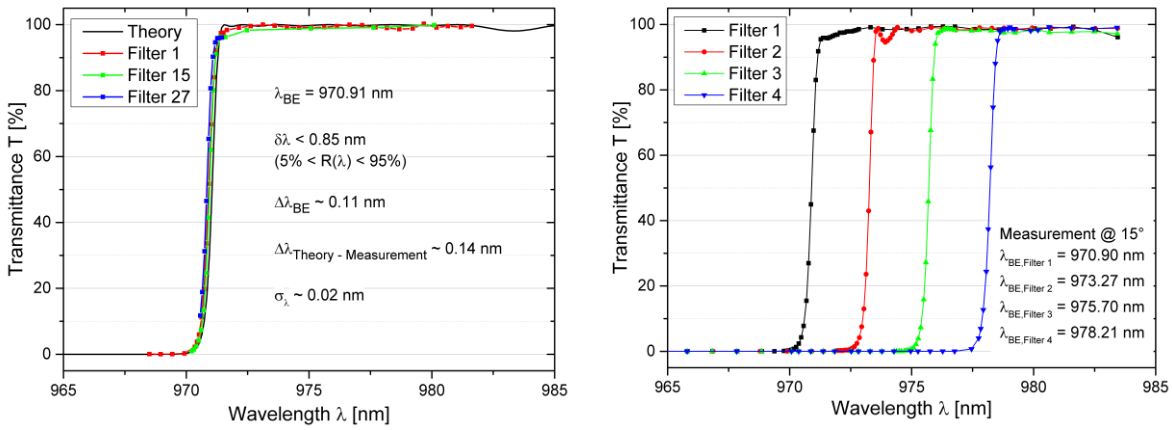


Fig. 8 Transmittance as a function of the wavelength for 3 filters of type 1 (HR 970 nm, HT 972 – 980.5 nm) (left) and comparison of the band edges for the four different types of filters used for the BRIDLE project.

Experimental results based on DFB mini bars

First experiments were performed with one diode laser bar. Due to parasitic back reflections, scattering losses, depolarisation of the diode laser sources and misalignment of the filters, a multiplexing efficiency of 65% was measured. Fig. 9 summarises the coupling efficiency (left) and the spectra of the internally stabilized diode laser (right). Equipped with four diode laser bars and polarization coupling, the module reached an output power of 46 W out of a 35 µm fiber (NA <0.2). For this demonstrator, scattering losses were reduced from 17% to approximately 5%.

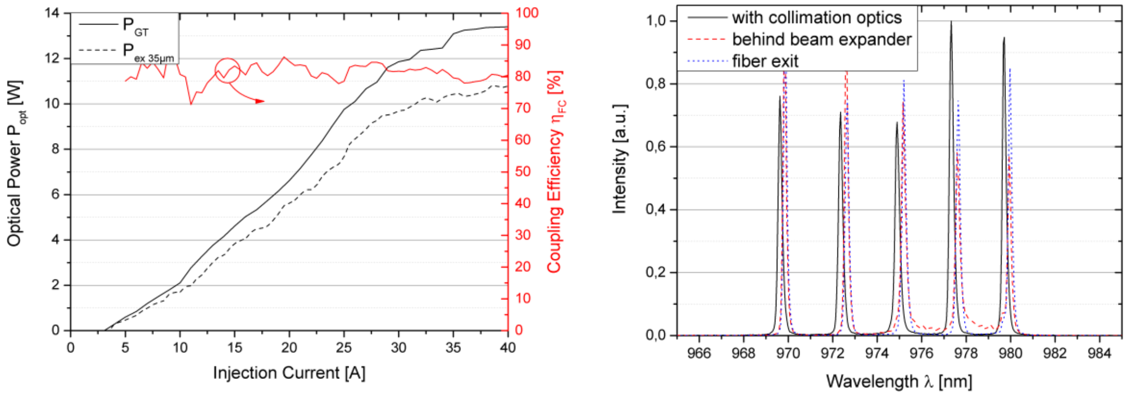


Fig. 9 Fiber coupling efficiency (left) and Spectrum of the DFB mini-bar (right). [1]

Experimental results based on externally stabilised mini bars

For the module based on 2 externally stabilised diode laser bars, an optical output power of 32.2 W was measured behind the telescope. Again main losses are caused by scattering, depolarisation of the diode laser bars and misalignment. Furthermore, cross talk between neighbouring emitters arose. The module was equipped with 2 diode laser bars, and coupling efficiency of 80% was achieved (Fig. 10).

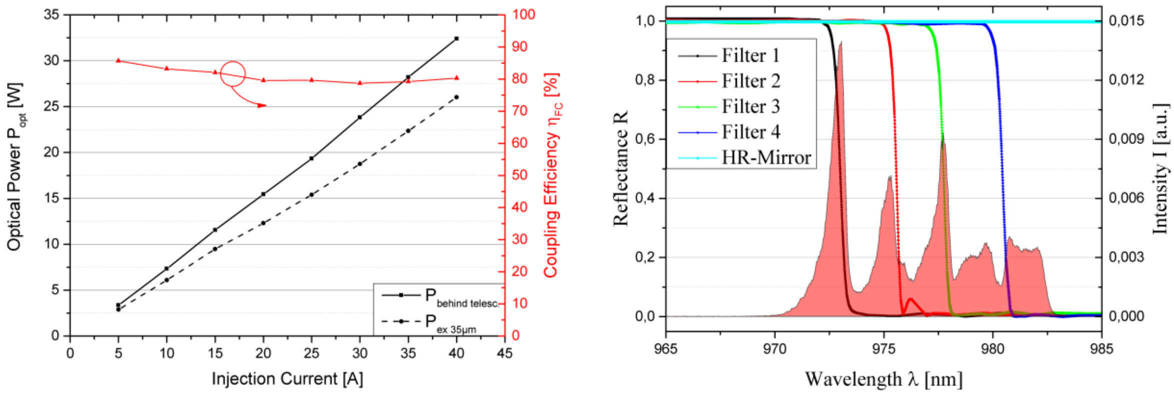


Fig. 10 Fiber coupling efficiency (left) [2] and Spectrum of the externally stabilised mini-bar (right) [1]. The setup was equipped with two diode laser bars.

Approaches for further power scaling and miniaturization

Within the BRIDLE project, the latest iteration of DFB diode laser mini-bars could not be integrated into a demonstrator due to delays in the course of the project (delivery of the bars post project in March 2016). According to modelling results, an output power of 65 W can be expected, in case the new bars should be >95% TE polarized. The setup of the module equipped with polarizing multiplexing is shown in fig. 11 (left). The two concepts for compact setups depicted on the right hand side offer reduced scattering losses.

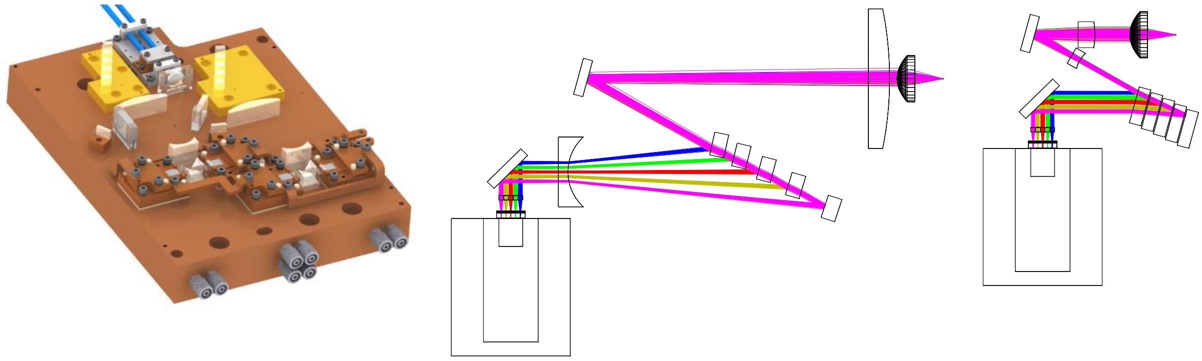


Fig. 11 Opto-mechanical design including polarization coupling (left). Two alternative approaches to overcome scattering losses at the side faces of the filters and to reduce the foot print based on one filter type only (centre) and on a double path configuration (right) [2].

Fiber combiner

For power scaling of the developed fiber coupled modules with 35 µm fiber, a 7:1 fiber combiner was developed and qualified. Compared to free space approaches, the integrated fiber combiner needs far less optical and mechanical components, is more robust and compact and offers the potential of cost-efficient mass production. Fig. 12 shows the concept of the integrated fiber combiner.

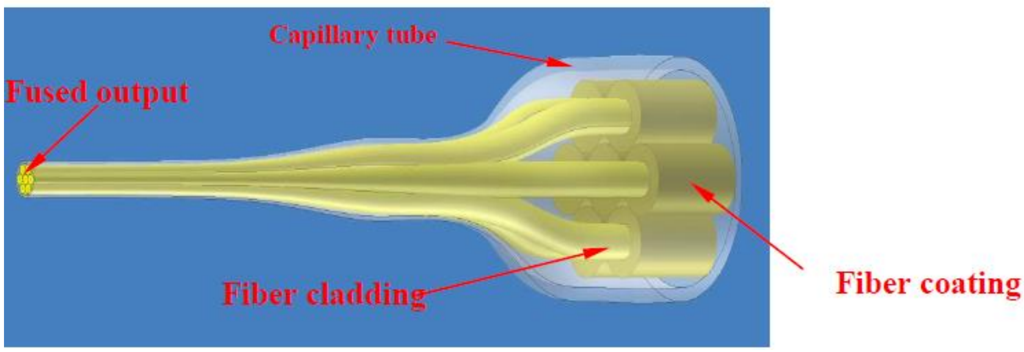


Fig. 12: Schematic of a fused fiber combiner. Source: "Review of fabrication techniques for fused fiber components for fiber lasers", Vytran LLC, SPIE Photonics West 2009.

The input port consists of 7 fibres (35 µm core diameter, 50 µm cladding, NA 0.12), which are tapered to a diameter of 90 µm and spliced to one common output fiber (100 µm core diameter, 125 µm cladding, NA 0.2). The fiber combiner is designed to withstand an input power of 100 W per channel, and an efficiency of 85% was measured. In fig. 13, the facet of the fiber bundle (left) and the near field view of the fiber bundle (right) are depicted.

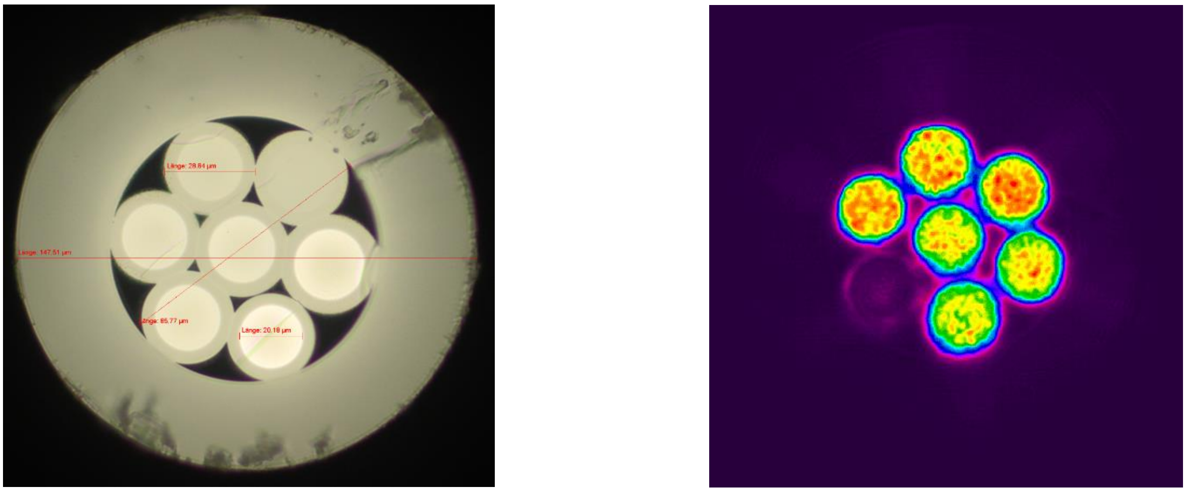


Fig. 13: Microscopic view of the fiber bundle (left). Near-field view on CCD camera (right; one port not operating).

References

[1] Witte, U., Rubel, D., Traub, M., Hamann, M., Hengesbach, S., Hoffmann, D., "Dense Wavelength Multiplexing and 35 µm-Fiber Coupling of Wavelength Chirped High Power Diode Laser Bars," Advanced Solid State Lasers (ASSL) Congress, AF1A.6 (2015)

[2] Witte, U., Traub, M., Di Meo, A., Hamann, M., Rubel, D., Hengesbach, S., Hoffmann, D., "Compact 35 µm Fiber Coupled Diode Laser Module Based on Dense Wavelength Division Multiplexing of NBA Mini-Bars," Proc. SPIE (2016).

[3] Witte, U., Hamann, M., Di Meo, A., Rubel, D., Traub, M. Hoffmann, D., "High Power Diode Laser with 23W ex 35 µm Fibre," Proc. IEEE 2015 High Power Diode Lasers and Systems Conference (HPD) 2015 (2016).

1.3.3 Coherent beam combining approaches

Coherent beam combining (CBC) is a technique that aims at increasing the spatial brilliance of laser sources. It consists in maintaining a constant phase relationship between different emitters, in order to combine them constructively in one single beam. Within BRIDLE, we investigated a new CBC architecture, which is based on the separation of the phase-locking and coherent beam combining of the lasers: the phase-locking is achieved passively in an extended cavity on the rear facet of the lasers, and the coherent combining is realized on the front facet (Fig.14). The goal of this architecture is to improve the electrical-to optical efficiency of the passive extended-cavity configurations, since the optical losses on the front side of the lasers are minimized. Moreover, such an extended cavity placed on the rear side of the emitters provides the strong optical feedback required for phase-locked operation. This new architecture was first demonstrated with two emitters in a Michelson-type extended-cavity, then scaled to bars of N = 5 and N = 10 devices.

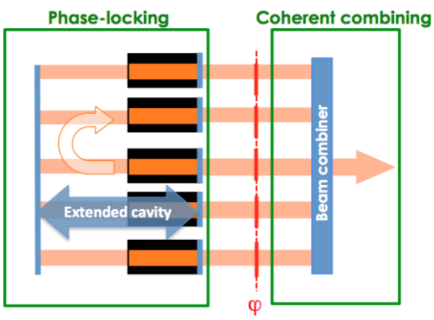


Fig. 14: Passive CBC architecture investigated within BRIDLE

The BRIDLE project partners provided two kinds of laser devices: single-mode ridge waveguide emitters by Modulight, and high-brightness tapered devices by FBH. Both devices were tested, and we could validate the rear-side extended-cavity architecture with both of them. In particular, we achieved a high power (6.7 W) from two tapered emitters passively phase-locked in a Michelson cavity (see fig. 15). The two beams were simply combined on a beamsplitter on the front side. We have demonstrated that the beam quality of the emitters was improved by the cavity to $M^2_{4\sigma} \leq 1.3$, and obtained a combining efficiency of 82% - up to 92% taking into account the proportion of the fundamental mode in the laser profiles. In order to maintain the combined power at its maximum over the long term, we implemented an automatic correction of the driving currents of each ridge section based on an iterative random exploration of the operating points around their nominal values. By doing so, we could compensate for brutal phase-shifts on the front side resulting from a frequency mode-hop of the extended cavity, and for any perturbation of the phase-locking process on the rear side.

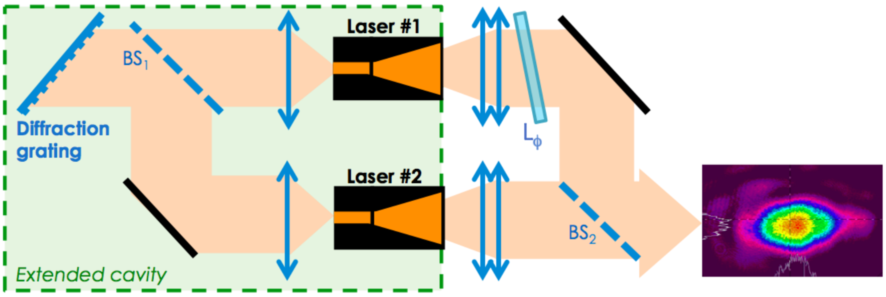


Fig.: 15 Michelson extended-cavity for the passive phase-locking of two emitters; BS_1, BS_2: beam-splitters; L_ϕ: silica plate for adjustment of the front-side phase shift; insert : beam profile on the combined arm.

Then we explored the scalability of our architecture with a single bar of emitters. For this purpose, ILT has designed and manufactured specific individually-addressable laser mounts, giving access to both facets of the bar and ensuring a proper thermal management of the lasers; the laser arrays were soldered by DILAS and connected by ILT. Two different extended cavities were investigated, which were suited to the two kinds of laser bars developed by Modulight and FBH respectively. We achieved the best results with a bar of five tapered emitters, with a pitch of 1 mm. This extended-cavity was based on a diffractive combiner (DOE) in an interferometric multi-arm configuration (Fig. 15). The DOE was a continuous phase-profile grating designed at CNRS-IO that provides diffraction efficiency as high as 99% in five orders with specific phases. Identical devices were used as a splitter/combiner in the rear extended-cavity, and as a coherent combiner on the front side of the laser bar. The passive phase-locking of the laser bar was obtained up to I_T =5 A (per emitter). A standard stochastic-gradient-descent optimization algorithm was implemented to find the proper currents in the five ridge sections that ensured the maximum combined power on the front side; also it could stabilize the output power within 0.5% RMS for hours. Under these conditions we achieved a maximum combined power of 7.5 W in a single beam on the front side of the laser bar. To our knowledge, the optical power reported here was the highest achieved in a single beam by coherently combined diode lasers using a self-organized extended cavity.

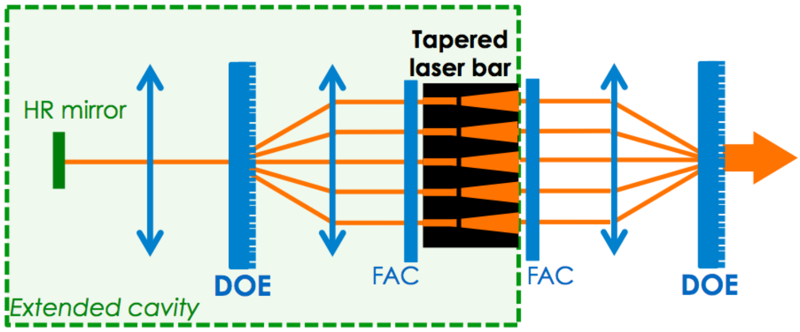


Fig.: 16 Multi-arm extended-cavity for the passive phase-locking of a bar of five tapered emitters; DOE: diffractive optical elements; FAC: fast-axis collimators.

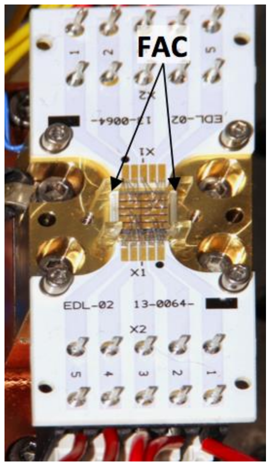


Fig. 17 Close view of the individually-addressed laser bar, with FAC lenses glued on each side.

Eventually we have investigated a fully-active MOPA configuration, with the same tapered laser bar and diffractive optical elements but a DFB seed laser diode injected into each emitter. The DFB laser diode ensured the relative coherence of the amplified beams, and the combined power could be maximized by continuously adjusting the currents in the ridge section of each emitter. This was a more traditional CBC configuration, which required an additional single-frequency laser source. Then we could increase the currents in the tapered sections up to 6A and get a combined power of 11.2 W, corresponding to a combining efficiency as high as 76%. It was limited on one hand by the beam quality of the tapered emitters and on the other hand by the fast phase fluctuations which could not be corrected by our optimization algorithm. Still, these results have confirmed the potential of coherent beam combining approaches with individually-addressed tapered laser bars to provide a high-power and high-brightness beam, and compare with the current state-of-the-art with laser diodes.

In parallel to this experimental work, CNRS-IO and UNOTT have worked together on the numerical modeling of the phase-locking process in an extended-cavity, based on a dynamic simulation tool developed at UNOTT, and on its coupling with a Fourier-optics model of the extended cavities. These efforts are described in the next section (WP5).

1.3.4 External cavity laser simulation

Work package 5 was responsible for the simulation and design of lasers for use in spectral and coherent beam combining. This work package was led by the University of Nottingham (UNott), but included inputs and interactions with CNRS Institut d'Optique (CNRS-IO), the Ferdinand Braun Institute (FBH) and Modulight. The first task of the work package focussed on the design and performance optimisation of laser diodes operating in an external cavity using a new multi-parameter design optimisation process. This used the careful calibration of the simulation tools and their validation against experiment carried out in a second task. FBH saw beam quality degradation at high output powers as a critical factor in tapered lasers for spectral beam combining, so a further task focused on identifying the mechanisms responsible for beam quality degradation and proposing methods to suppress it. Investigations of external cavity feedback on the operation of large optical cavity tapered lasers confirmed the new design optimisation process and provided new insight into the role of non-lasing higher order vertical modes. The final task of the workpackage was devoted to the most challenging modelling activity in *BRIDLE* – the development and demonstration of a new and unique quasi-3D dynamic simulation tool for the investigation of phase-locking processes (and their disruption) in coherent beam combined laser systems. The results of WP5 have generated four invited talks and an invited book chapter.

UNott's multi-parameter optimisation process (Fig. 18) started with the identification of vertical waveguide structures with: high modal discrimination to suppress the excitation of higher-order vertical modes; a wide vertical near-field for efficient external cavity coupling, relaxed alignment tolerance, reduced optical aberration (allowing the use of simpler optics). Next, 1D and 2D simulations were performed to maximise their electrical-optical power conversion efficiency (PCE).

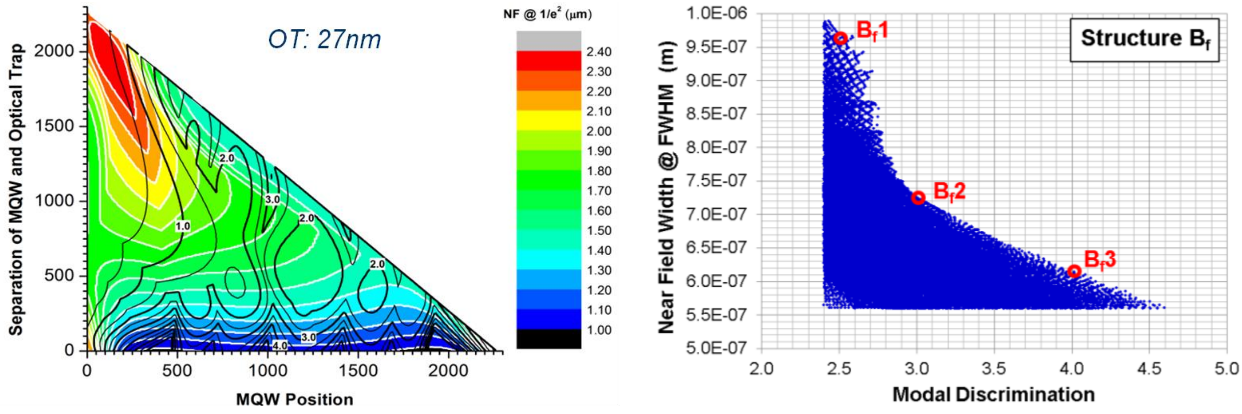


Fig. 18: Dependence of the near-field (NF) width (colour contours) and modal discrimination (MD) (black contours) on the position of the MQW relative to the p-cladding layer and the optical trap (left); Trade-off between NF width and MD (right).

UNott's laser simulation tool (*Speclase*) was calibrated for the devices fabricated by Modulight and FBH. The calibrated simulation tools were then used to assess, optimise and provide improved design recommendations for ridge waveguide lasers to Modulight (Fig. 19).

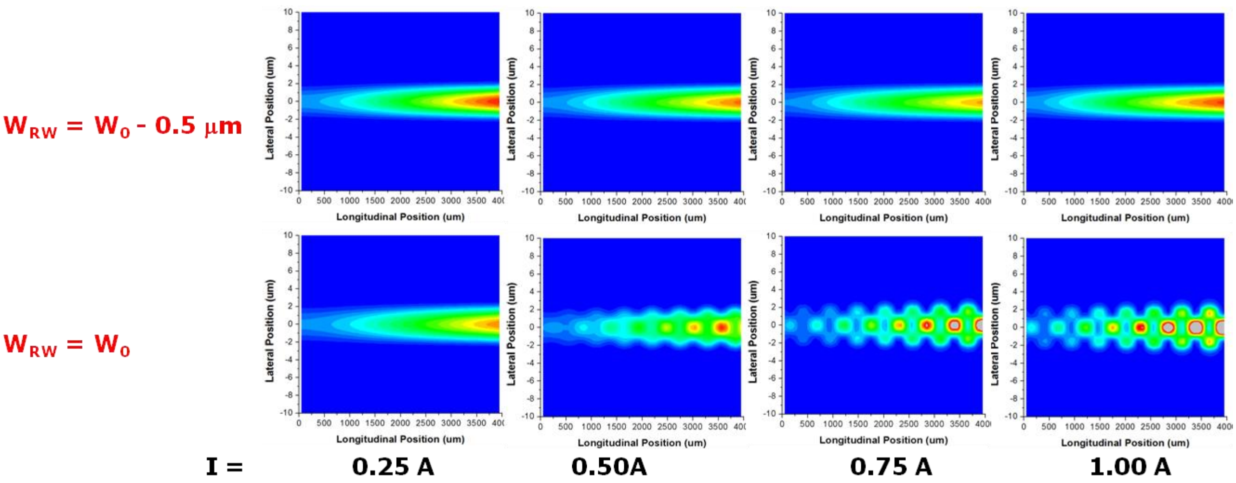


Fig. 19 Optimisation of the ridge waveguide design to ensure single lateral mode emission under high power operation.

This multi-parameter optimisation procedure was also used for FBH's ELoD2 tapered DBR lasers, showing that a thinner waveguide could be used to simultaneously increase the power conversion efficiency and modal discrimination, but at the expense of an increase in fast axis far-field divergence (Fig. 20).

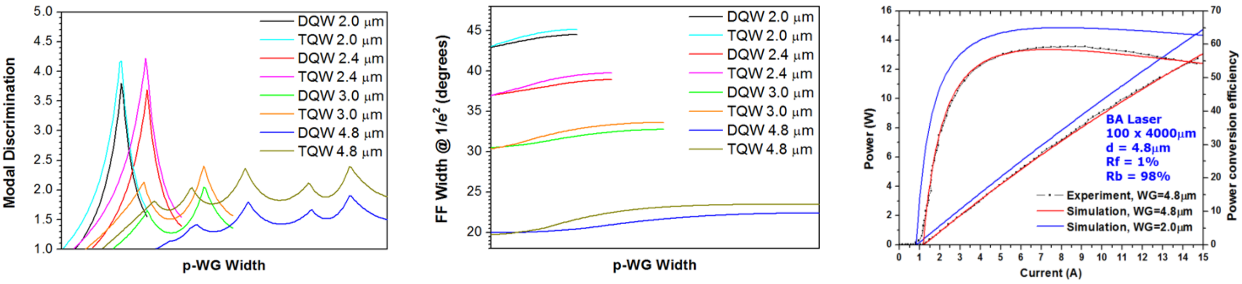


Fig. 20: Modal discrimination (left), far-field (centre) and L-I/PCE-I characteristics (right) of selected vertical structures.

Next, UNott investigated the beam quality degradation of DBR tapered lasers based on FBH's thinner ASLOC laser epitaxy – focussing on the dependence of the ridge waveguide filter performance on ridge width, etch depth and bias current. The spatial ridge waveguide filter function (ratio of forward and backward propagating power distributions at the ridge-taper interface) was proposed as a new figure of merit for the performance of the ridge waveguide filter. (The ratio between the centre and side lobes gives a measure of its performance.) The filter function of the ridge waveguide was found *not* to depend on either the width or the etch depth of the waveguide, but rather on the ridge waveguide current (Fig. 21). The centre/side lobe ratio increases with increasing ridge waveguide current, as did the linearity and slope efficiency of the L-I curve and the PCE.

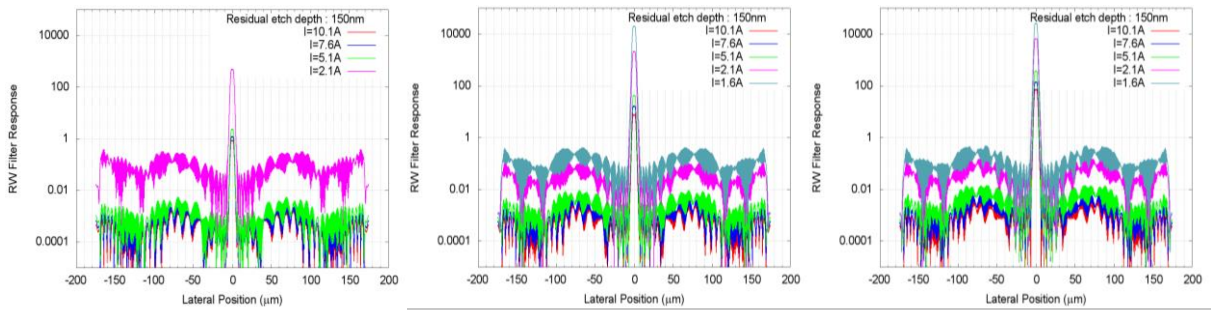


Fig. 21 Ridge waveguide filter function as a function of RW current: 50mA (left); 125mA (centre); 300mA (right).

A CW simulation tool for external cavity laser diodes was developed by self-consistently coupling UNott's quasi-3D laser simulation tool (*Speclase)* with a commercial optical modelling tool (*Zemax*). Using this tool, UNott investigated the effect of external cavity reflections on the performance of a large optical cavity tapered laser diode and how this was affected by the excitation of higher order vertical modes. The external feedback was found to reduce both the slope efficiency and the power conversion efficiency and could even facilitate the lasing of higher order vertical modes (Fig. 22).

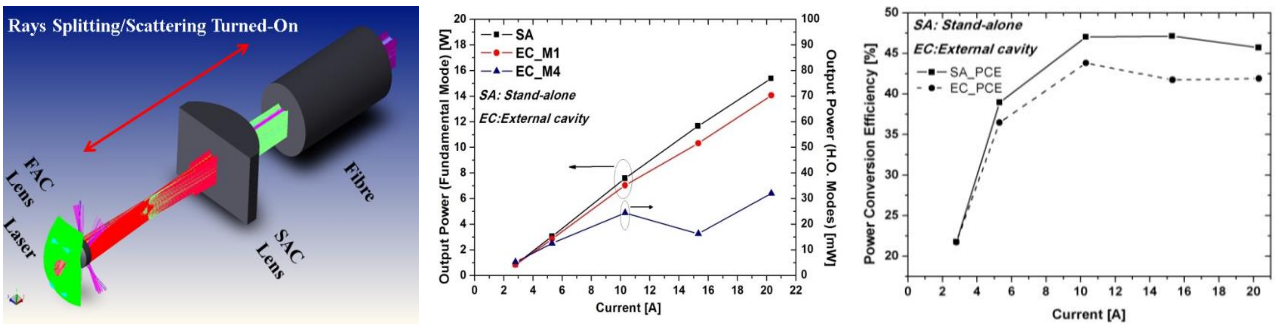


Fig. 22 Impact of external feedback on an LOC tapered laser: experimental structure (left); L-I curves (centre); PCE (right).

The lasing of higher-order modes results in current competition, additional heat generation (e.g. Joule heating, free carrier absorption, optical pumping of the RW absorber) and increased beam parameter product (Fig. 23). The coupling of optical power into the *non-lasing* vertical modes also has an effect on the laser performance, contributing to absorption bleaching in the RW section and heat generation.

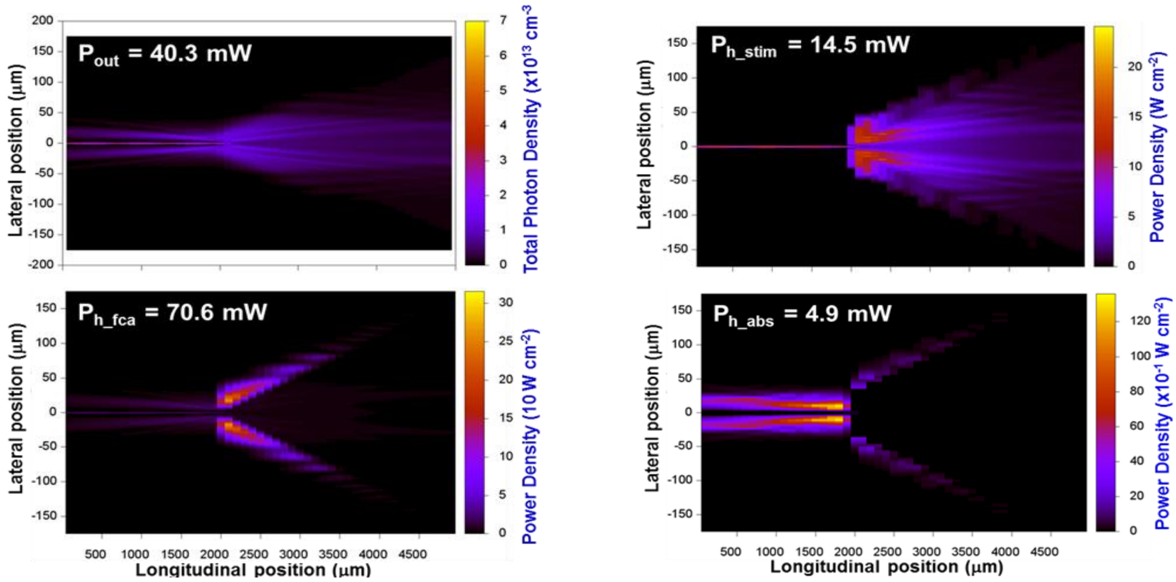


Fig. 23: Impact of parasitic high order vertical mode lasing: photon distribution of the mode (top left), Joule heating due to stimulated emission current (top right); free carrier absorption heating (lower left); and optical pumping (lower right).

This investigation also showed that a high modal discrimination is better at suppressing the excitation of higher order modes than reducing their external cavity coupling strength.
UNott also extended their time domain laser simulation tool (*Dynlase*) to a quasi-3D model by including a 2D time-domain optical solver (validated with a passive DBR ridge waveguide structure). This model was developed to simulate FBH's narrow broad-area DFB lasers and the phase-locking processes in CNRS-IO's coherent beam combining systems. We believe this is the first quasi-3D dynamic laser simulation tool capable of self-consistently modelling temporal, spatial and spectral effects, which does not use the single wavelength eigenmode expansion and which can be used to include waveguide/material dispersion and localised spatio-temporal effects (e.g. nonlinear optical effects). Fig. 24 (left) shows initial results for a 400µm ridge waveguide Fabry-Perot laser diode operated below threshold. The position, linewidth and relative strengths of the resonances are consistent with the Fabry-Perot resonances and the spectrum of the injected optical pulse. Spontaneous emission was then included in the model to facilitate self-organised lasing. Fig. 24 (right) shows a single-lobed spectrum from the Fabry-Perot laser when biased at twice the threshold current.

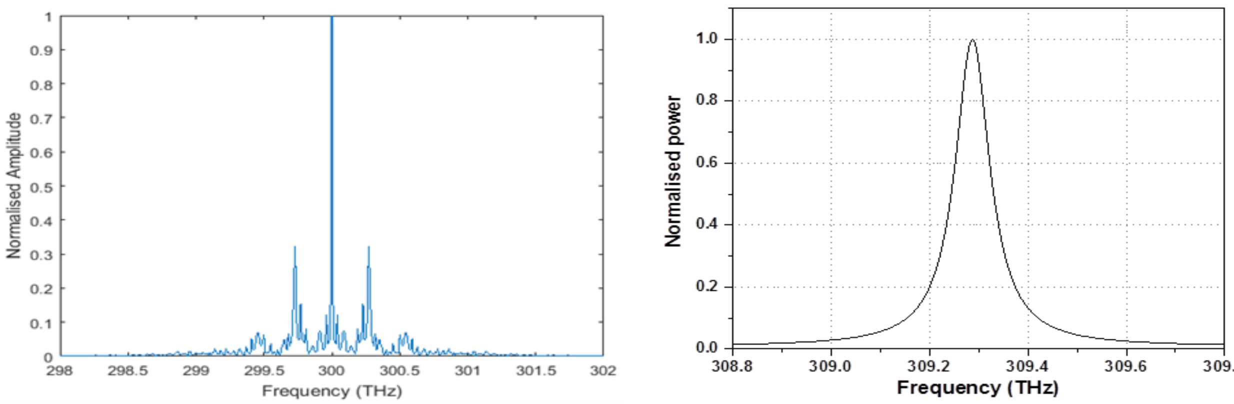


Fig. 24 Dynamic simulation of a 400µm Fabry-Perot laser. Output spectrum: below threshold (left); above threshold (right).

UNott and CNRS-IO developed a self-consistent spatio-temporal software algorithm for the CBC cavity, building on CNRS-IO's cold-cavity Fourier optics model. The cold-cavity model was intended to describe the behaviour of the extended cavity and predict the selected supermode profiles, their effective reflectivity and the discrimination between them. It was used with the two kinds of cavities (an interferometric multi-arm cavity and a Talbot self-imaging cavity) experimentally investigated with laser bars within *BRIDLE*.

1.3.5 System design and integration

In BRIDLE, DILAS developed several incoherently coupled direct diode laser modules, for example the 400W "BRIDLE-I1" based on bars delivered by FBH.

All high power modules and subsystem have been built on the basis of the established tailored bar ("T-Bar") platform at DILAS that is used as an industrial standard since several years.

The main system architecture consists of a horizontal stack of seven or more 5mm wide diode bars operated electrical in series. The diode bars are soldered onto isolating ceramic sub-mounts and 7 (or more) of this sub-mounts are then soldered to a common water cooled copper heat sink. For the 400W module two of these modules with 7 diodes each are coupled with polarization combining. A more detailed description of the module can be found in deliverable report D6.1 and Milestone MS18 report.

DILAS has adapted the commercially proven fabrication process to enable the fully automated handling of the BRIDLE laser diode bars within the T-bar platform, which means that at the end of the project, the modules with one or two base plates, currently up to 300W from a 100µm fiber are production ready (TRL 6/7).

Module description

The main system architecture for the high power scaling consists of a horizontal stack. The design starts with defining ("tailor") the lateral (slow-axis) beam quality by choosing bar width, working point of the output power curve, emitter size and pitch to fit the laser fiber used for application. The vertical (fast-axis) beam parameter product is then filled by adding more laser bars with optical stacking.

This "dense spatial multiplexing" of the output power of for example seven bars is achieved by first collimation the output power with fast axis (FAC) and slow axis (SAC) collimating lenses and a 90° turning mirror in slow direction which redirects each diode to achieve an optical stack of the bars in the fast axis direction.
The stacking pitch is then controlled by the vertical turning angle of the redirection mirror and can be adapted to the collimated fast axis beam width which is given by the FAC focal length and the fast axis divergence of the diode bar.

This leads to a dense packed, nearly rectangular beam with similar beam parameter products in slow and fast direction, which may be coupled into a transport fiber with the use of a single circular coupling optic. After alignment, the resulting bases plate are electro-optically characterized and analysed as to beam quality and fiber coupling efficiency.

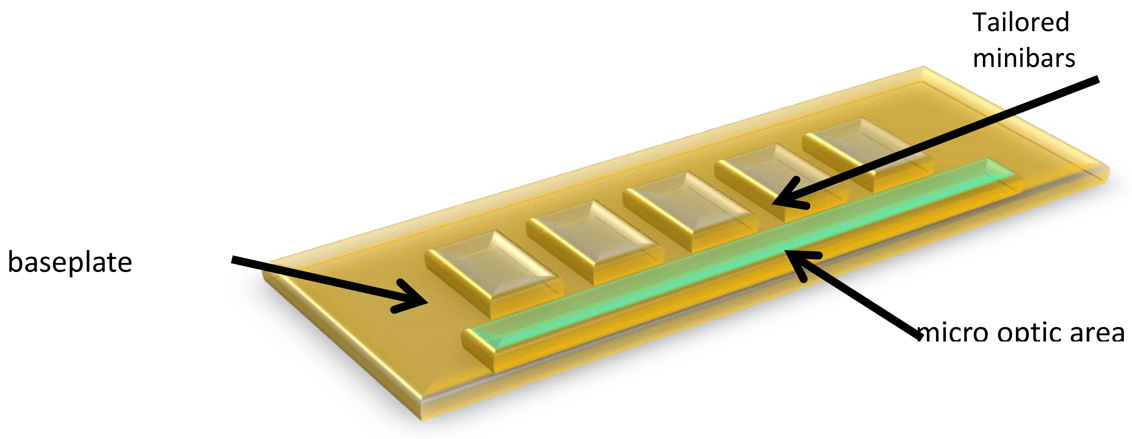


Figure 25 Seven bar base plate for the 400W subsystem, symbolic arrangement

Figure 24 shows the LIV curve of one of the improved base plates and a caustic scan (based on the second moment method) of a typical plate at a drive current of 30A. From these base plates, 185W at a conversion efficiency of 55% at 30A are reached.

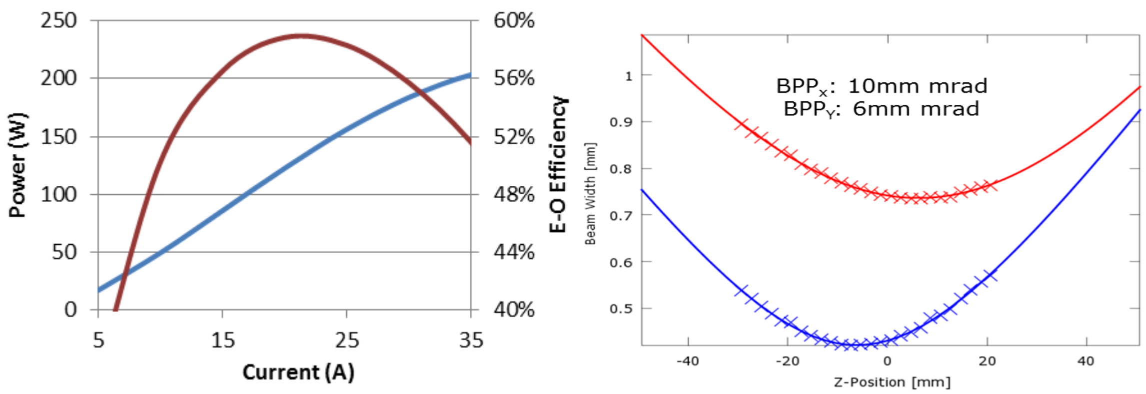


Fig. 26 Left: LI curve of the base plate with 7 bars (blue) and efficiency (red). Right: corresponding caustic scan based on the second moment method

Two of these base plates can be coupled via polarization coupling leading to a combined power of more than 300W from a 100µm NA0.2 fiber. Figure 25 shows the resulting LIV curve. The coupling efficiency at 30A was determined to be 72%. Main improvements can be achieved with an improved degree of polarization and a lower slow axis divergence (~7° at >7W output power per emitter).

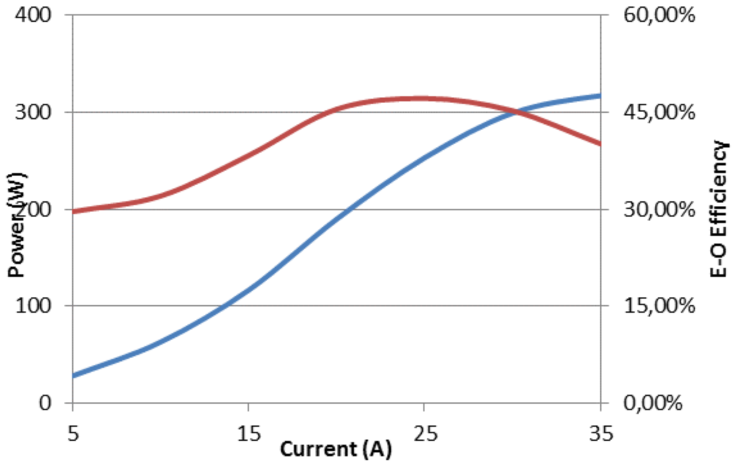


Fig. 27 LI curve of the fiber coupled beam source with two base plates and coupling to a 100µm NA0.2 fiber

The two base plates are integrated into a DILAS standard housing that was adapted for the realisation of the fiber coupled laser source. Figure 28 shows the resulting laser.

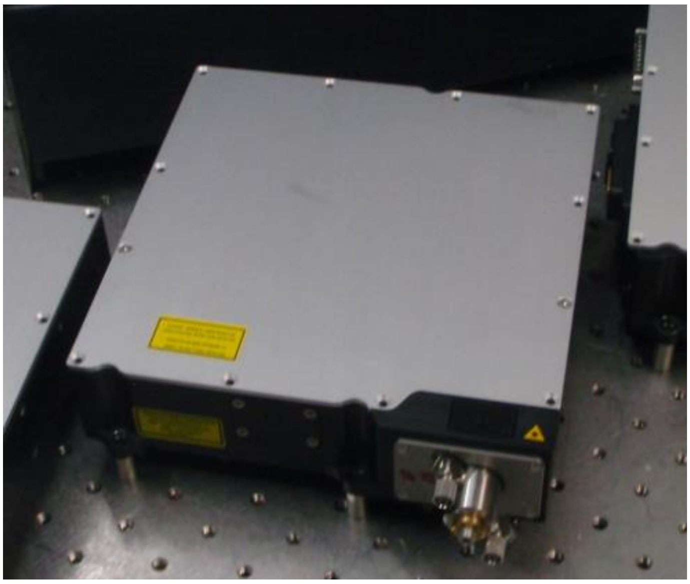


Fig 28 300W diode laser module with 2 base plates inside and a total of 14 laser diode bars, equipped with BRIDLE bars.

To reach the project goal and realize a kW class direct diode laser system for cutting application, an alternative scaling concept using dense wavelength multiplexing was realized. The baseplates delivering up to 200W output power each are wavelength stabilized with external gratings (VBG).

For coupling multiple base plates at one central wavelength around 976nm, a wavelength spacing of 4nm was chosen. A demonstrator setup with three baseplates was built. In a first setup, 3 plates are wavelength stabilized with VBGs at 972nm 976nm and 980nm (Fig. 29 left side) with a linewidth of the modules smaller than 0.5nm. These three plates were than coupled with commercially available dichroic mirrors with an edge steepness of ~1nm. Angle tuning of the dichroic mirrors was used to achieve optimum coupling efficiency. Figure 29 (right side) shows the simulation with Zemax raytracing software and the resulting setup.

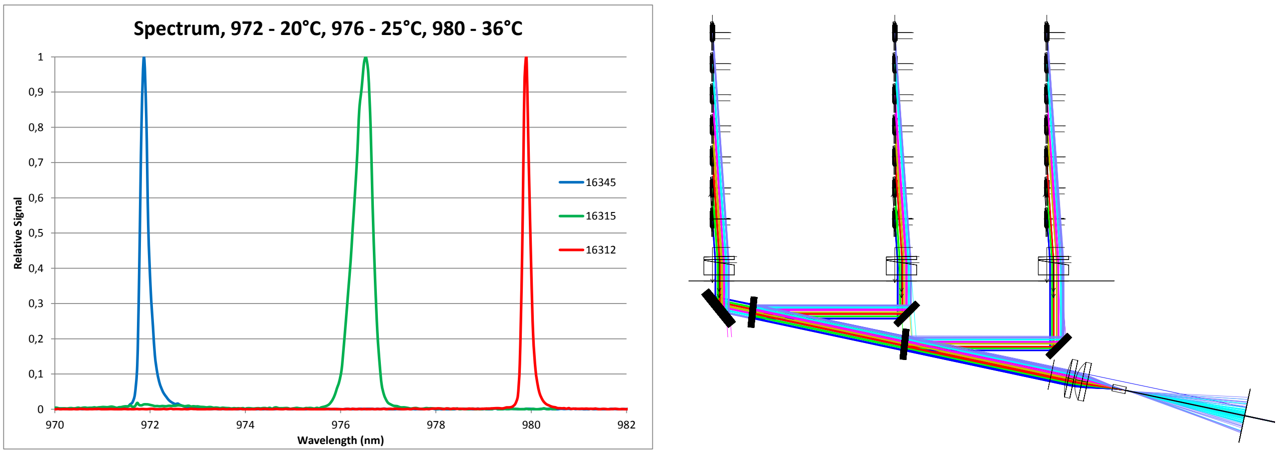


Fig.29. Left: spectra of the three wavelength stabilized base plates Right: Zemax simulation of the wavelength coupling prototype

In Fig. 30 the output power after the coupling of the three plates into a 100µm NA0.2 fiber is shown. An output power of 410W at 35A was achieved. Since all of the optics for this setup were commercially available stock optics, performance of the system was not ideal in this case and ~40% power conversion efficiency was reached. Simulation calculations showed, that with optimized micro-optics one can expect 500W of output power with >45% electro-optical efficiency. This three-plate setup still has a linear polarized output beam and the output power can be doubled to up to 1kW at a single central wavelength. Conventional coarse wavelength coupling can then be used to achieve several kW of output power from a 100µm fiber.

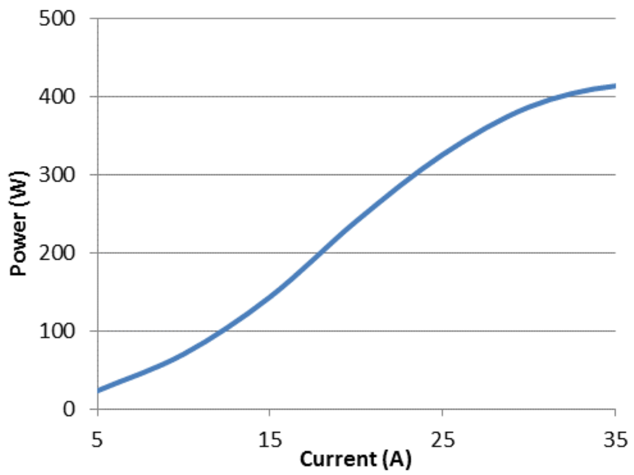


Fig. 30: LI curve of the fiber coupled prototype with three base wavelength coupled plates and coupling to a 100µm NA0.2 fiber

The dense wavelength coupling scaling concept was able to fulfil the project goal of a >400W coupled into 100µm NA0.12 fiber module at one wavelength. A second prototype system around 940nm, again with three wavelengths coupled at a dense distance of 4nm, was realized and added to the 980nm system.

1.3.6 High-power demonstrator system

A system based on incoherent beam combing (IBC) was set up as the final demonstrator system, suited for sheet metal cutting. See fig. 31 for the conceptual layout of the system.

The system consists of 2 wavelength ranges (94x nm and 97x nm), and for each wavelength range, three dense wavelengths are coupled by dense wavelength division multiplexing. Thus the system consists of 6 modules equipped with tailored mini bars suited for efficient fiber coupling (100 µm, NA 0.15). After dense and coarse wavelength division multiplexing, the laser beam is symmetrized by cylindrical optics and launched into a common 100 µm fiber.

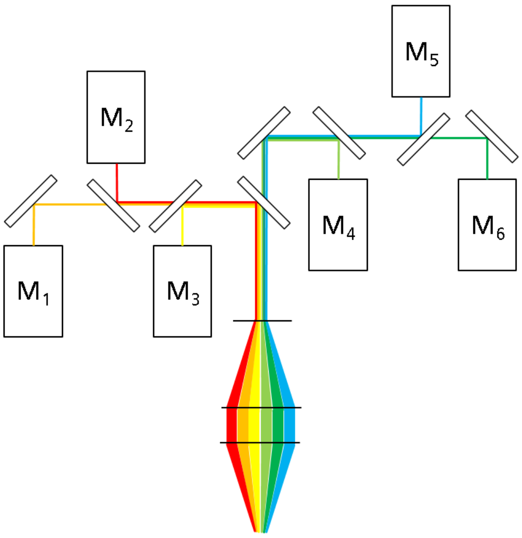


Fig. 31 Conceptual layout of the high power demonstrator consisting of 6 modules, arranged on two benches (M_1 to M_3: 94x nm, M_4 to M_6: 97x nm).

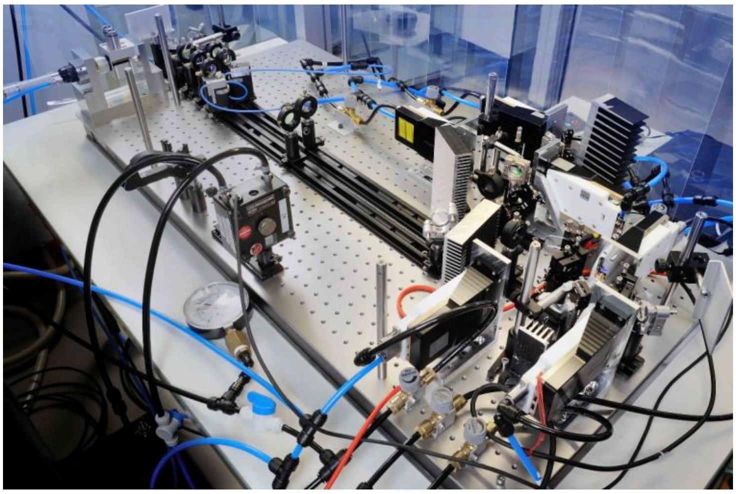


Fig. 32: Breadboard model of the final 800 W fiber coupled direct diode laser demonstrator.

In Fig. 32 the setup of the demonstrator on a breadboard is shown, where six submodules are coupled.

Fig. 33 shows the LI curve of the final demonstrator. The sum of the maximum output power of the individual modules amounts to 1.25 kW, and an output power ex fiber of 800 W was measured. Main losses occur at the polarization coupling, at the wavelength multiplexing devices and at the optical fiber. However, the output power is sufficient for efficient cutting of thin metal sheets, and the output is higher than the best commercially available system that is based on a comparable technology.

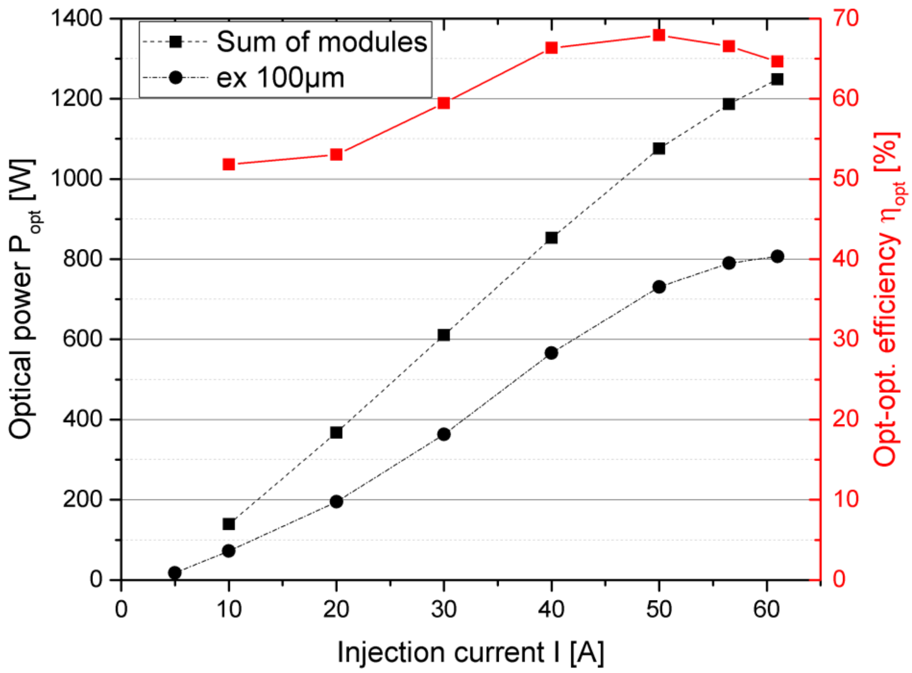


Fig. 33: LI curve of the demonstrator.

1.3.7 Application of the diode laser system

Sheet metal cutting

The final demonstrator was successfully integrated into a cutting system. The cutting head was mounted on a gantry robot system. The cutting head was equipped with a collimation with 120 mm focus length and a focusing optics with 220 mm focal length which corresponds to a magnification of 1.8. The laser itself was mounted onto a breadboard and protected against environmental damage by use of a mobile flow box.

Focus position and cutting speed were adjusted to obtain maximum cutting speed and quality for cutting stainless steel with sample thicknesses of 1 mm and 2.5 mm. Results for stainless steel are comparable to results obtained with state of the art fibre lasers with the same output power.

Fig. 34: Metal sheet cutting experiment (stainless steel, d = 2.5 mm, v = 18 mm/s, N_2 gas).

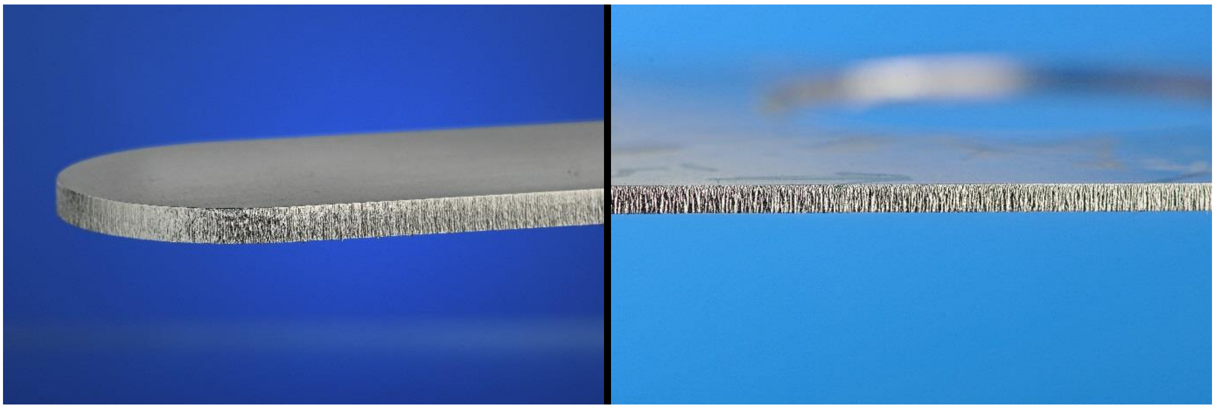


Fig.35: Cut edge for 2.5 mm (left) and 1 mm (right) stainless steel.

The output power and beam quality of the last BRIDLE demonstrator based on DWDM, polarization coupling and CWM is sufficient for efficient cutting of thin metal sheets and suited at least for thicknesses up to 2.5 mm. The system performance results in reproducible cuts. Back reflections resulting from badly chosen cutting parameters do not lead to a degradation of the system.

A video with the laser cutting is available at the Bridle website: www.bridle.eu

Selective Laser melting (SLM)

In order to evaluate the applicability of the developed beam sources for Additive Manufacturing (AM), more specifically in a novel Selective Laser Melting (SLM) system, the following investigations were carried out:

- General beam source characterization:
  Determination of the characteristic curves of all diode laser modules, maximum output power and deviations/alterations in the characteristic curve of the first module over a 4 month period

- Comparison of possible application in conventional SLM and novel exposure concepts
- Principal applicability investigation
  Analysis of single melting tracks (track stability and melting depth), single layer (melting track interconnection) and multilayer-buildup (sample density)

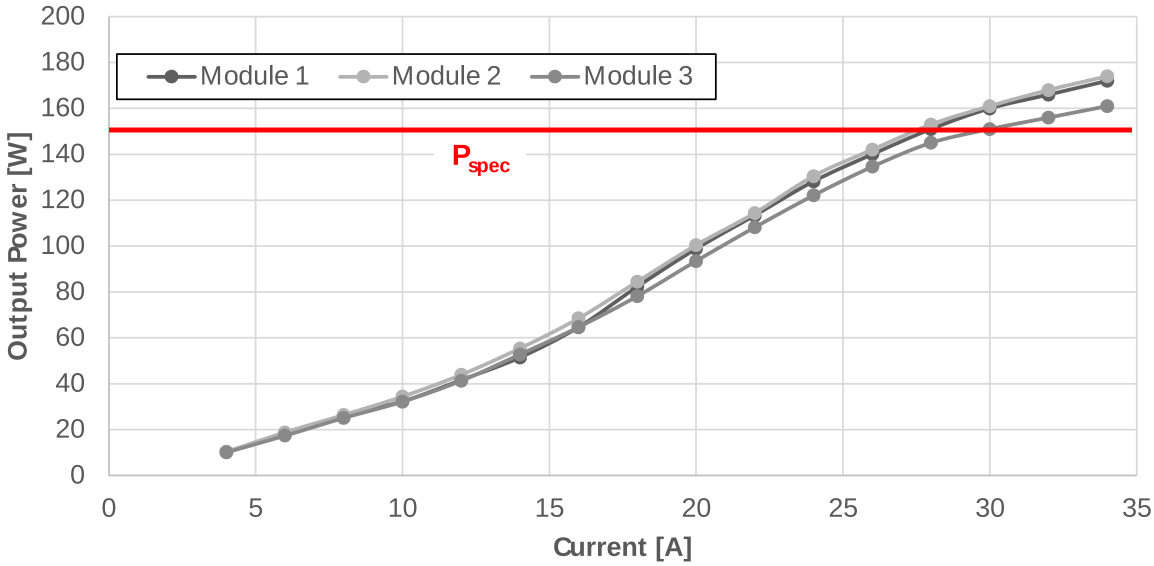


Fig. 36: Characteristic curves of the BRIDLE beam sources used in the SLM experiments

Summarized evaluation

During the investigations, it was determined that the modules' output power and power stability as well as beam quality are sufficient for an application in 3DLP-processes. The curves all show the same progression with only minor deviations (see Fig.7.). Comparison of output power measurements over the course of four months showed deviations only in the range of the power meter's measuring uncertainty, which implies a high degree of output power stability. Furthermore, the module-to-module-reproducibility and the similarity of the individual characteristic curves enable an easy integration into a multi-spot-system and the control software required therefor.

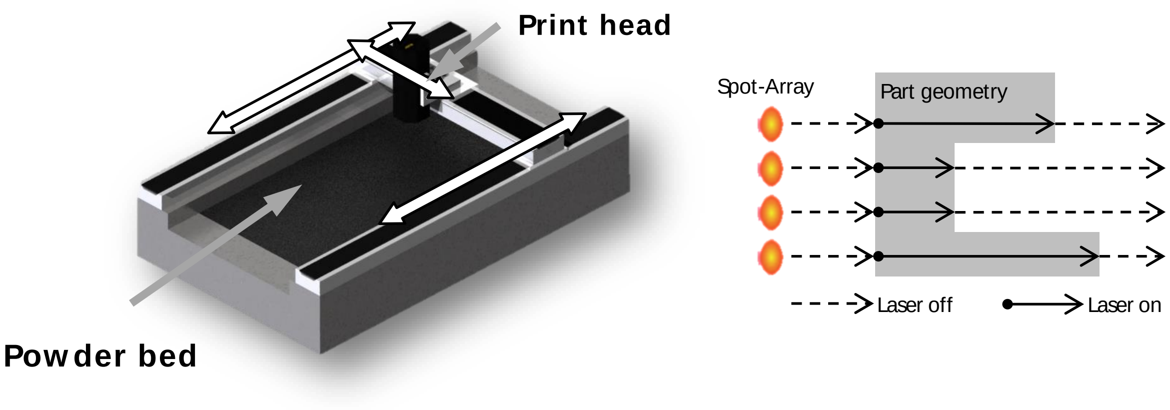


Fig. 37: Principle of the novel multi spot SLM process.

The laboratory application of BRIDLE beam sources in a novel SLM system (Fig) showed that melting tracks and multilayer samples can be produced with similar properties compared to conventional, fibre-laser based systems.

Next to the potential low-cost realisation of commercial diode laser modules based on the results of this project, the future scalability of the BRIDLE-module's output power paves the way towards an industrial application of diode lasers in future Additive Manufacturing systems with significantly increased productivity.

For more details, see:

U. Witte, F. Schneider, M. Traub, D. Hoffmann, S. Drovs, T. Brand and A. Unger, „kW-class direct diode laser for sheet metal cutting based on DWDM of pump modules by use of ultra-steep dielectric filters" Opt. Express, to be published.

U. Witte, F. Schneider, M. Traub, D. Hoffmann, S. Drovs, T. Brand and A. Unger, " kW-class direct diode laser for sheet metal cutting based on commercial pump modules ",Proc. SPIE, manuscript in preparation.

1.4 Future exploitation opportunities / potential impact

Laser Cutting

First industrial laser cutting systems were available in the 1980s with laser powers below 0.5kW based on a CO2 laser source. Since this time machine performance was growing with output power and reached with 6-8kW optical powers its maximum. Since 2010 the fiber laser penetrated the laser cutting market, starting with 2kW in the premium segment. Since 2014 6kW is state of the art and currently it is not clear, if there will be saturation in output power. On the other hand, the market for low power machines (such as ≤2kW) is almost negligible in the premium segment. From this point of view, DDL can only penetrate the cutting market with powers >2kW.

However in the low cost segment, especially on the Asian market, the majority of laser cutting systems is below 2kW. Here low-cost and easy-to-use lasers systems (such as DDL) could be highly interesting.

Since there is a fundamental correlation between output power, beam-quality and cutting speed, there is a lower limit in the brightness, which makes DDL interesting for metal cutting. Another limiting factor is the numerical aperture of the beam-shaping optics the incident angle into the process zone. Typical NAs are 0.08 and the limit is from todays view 0.12.

The 7xS5 laser source developed in BRIDLE with powers in the range of 0.5kW and a BPP of ~8mm*mrad, is not sufficient to address metal cutting. However the combination of several wavelengths (dichroic beam-combining) allows powers >1kW., which is seen as the threshold power to enter the macro material processing market with a diode direct laser.

Laser Beam Welding

In addition to traditional gas and resistance welding, laser beam welding has become a commonly used technique. It has various advantages compared to other welding techniques, e.g. it results in better quality and is easily to automate and state-of-the art in car manufacturing. Here the requirements on brightness are smaller than for laser cutting and first diode direct lasers are already in industrial application. With improved beam quality the application spectrum gets more flexible – currently deep-penetration welding is only possible with fiber-lasers or at very high powers. With a revenue for kW-class laser sources of ~300Mio$ this market is smaller than metal cutting. At this stage it is not clear, if laser based welding processes can displace the conventional welding methods and therefore growth rates are currently in the range of 5%.

SLM and Additive Manufacturing

For SLM, intensities in the range of 0.2 MW/cm² to 20 MW/cm² are applied (depending on material properties and layer thickness). The most commonly used process parameters achieve intensities between 2.5 and 10 MW/cm² in the powder-radiation interaction zone. With the BRIDLE-S5 module an optical output power of $P > 45$ W ex 35 µm was experimentally demonstrated by Fraunhofer ILT and output powers in the range of 70 W are feasible with the improved 4th iteration of the DFB diode laser mini bars and in case of 100% TE polarized diodes. This corresponds to an intensity of $I = 4.7$ MW/cm² to $I = 7.3$ MW/cm² at the fiber exit. Therefore, such modules are very interesting for micro SLM where spot sizes in the range of 25 µm to 40 µm are used.

Along with the development of a compact and economic fiber array that can be used as a print head, the BRIDLE-S5 modules would be a very promising beam source for multi spot SLM processing. None the less, before integration into SLM processing, several challenges still have to be overcome:

1. General process development for multispot-SLM and evaluation of potential economical advantages
2. Significant increase of electro-optical efficiency by mainly increasing the DoP of the emitters
3. Demonstration of a stable multiplexing efficiency in pulse mode
4. Economic production of the concept

Pumping of Ultra-Fast Lasers

Pumping with high brightness beam sources can significantly decrease the complexity of solid state lasers. The BRIDLE-S5 module offers a brightness that is a factor of 4 higher than state of the art pump sources. Furthermore, the output power is in the range of 20 W to 50 W. A lot of applications for ultra-fast lasers require only intermediate output powers in the range of five to a few tens of Watts (e.g. drilling and marking). I.e. pump modules with output powers in the range of 10 W to 50 W are often needed whereas most commercially available high brightness beam sources come along with at least 120 W (standard 105 µm pump modules with approx. 50 W do not achieve a sufficiently high brightness). Hence, the technologies developed for the BRIDLE-S5 module will enable new generations of ultra-low cost, compact and flexible ultra-fast pulsed laser systems.

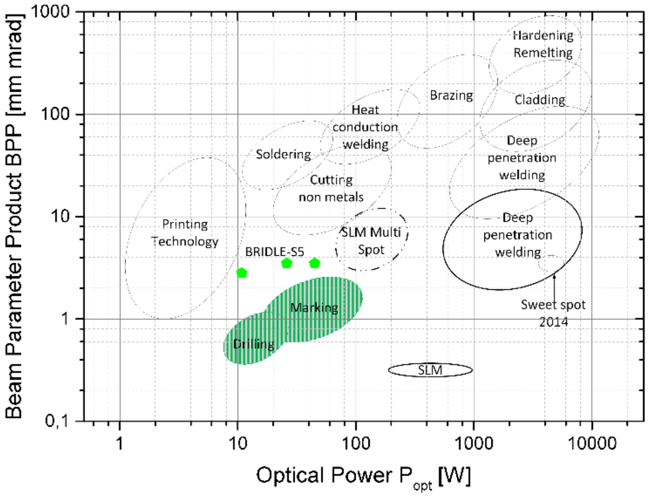


Figure 1: Beam parameter product and optical output power for different applications in the materials processing sector including two standard applications for ultra-fast lasers (drilling and marking). Source: Friedrich Bachmann: "Industrial applications of high power diode lasers in materials processing" (2003). The characteristics of the demonstrated BRIDLE-S5 modules are given for comparison.

Spectral widths of 10 nm are acceptable for pumping broadband laser crystals (e.g. Nd:YAG at 940 nm). However, other crystals or pumping wavelengths require frequency stabilized pump sources. Here again, 35 µm fiber coupling along with internally stabilized laser diodes can be very advantageous.

Laser Polishing

The tooling (moulds, dies and special tools) industry in Europe represents an annual turnover of 13 billion Euros. For the manufacturing of injection and die casting moulds, 12 to 15 % (1.5 to 2.0 Billion Euros) of the manufacturing costs and 30 to 50 % of the manufacturing time fall upon to the polishing. As current automated polishing techniques are almost not applicable for parts with freeform surfaces and function relevant edges like 95% of the tools, the polishing is predominantly done manually.

Laser and robot polishing offer the potential to strengthen the European Tooling Industry by a significant decrease of polishing costs (75%) and time (90%). In 5-7 years this will result in expected annual savings of manufacturing costs for tools of 150 Mio € and in reductions of the time-to-customer by 27% to 45% [http://www.automated-polishing.eu and proposal]. It can be expected that, in the coming years, the market share of laser polishing will increase from almost 0% today to at least 10%. This would correspond to a market of 150Mio€ per year. The market figures given above correspond to the whole polishing market, including the complete machines and salary.

In laser polishing, cw lasers with optical powers in the range of 50W to 800W and fiber diameters of up to 100µm (NA <= 0.15) are widely used. Currently only fiber, rod and disk lasers are used for high quality applications. Compared to the DoW, the demands have not changed. As described in the DoW, especially the the BRIDLE I1, the BRIDLE 7xS5 and the BRIDLE C3 offer the opportunity for direct diode laser polishing, addressing a market of presumable 150 Mio € per year in the near future (in ~5 years). The costs for the beam source itself can be estimated to be 10% of the complete market.

Laser welding of Polymers

Small parts made of polymers are welded with output powers of roughly 50 W. Especially in microfluidics this power regime together with a beam parameter product of 2 mmmrad or less is of special interest. As stated above, an intensity distribution that is close to a top hat, is of special interest for welding applications. The BRIDLE C1 module will be used in the TWIST process, where fiber lasers are used today. As this module can be built up only on a laboratory platform within the remaining time of the project, this cannot be demonstrated. On the other hand, the BRIDLE S5 module with an estimated output power of more than 50 W can also be used for welding applications of polymers (c.f. DoW, p. 6), especially in microfluidics. A comparison with and without the TWIST process can be made as well.

In addition to micro fluidics, glass-fiber reinforced plastics (GFRP) are joined by laser transmission welding with laser powers in the range of 100W ex 400 µm fiber. Cutting and trimming of these materials is possible with laser powers above 1 kW ex 105 µm fiber. The global market for manufacturing systems for fiber reinforced polymers (FRPs) was estimated to 340 Mio € in 2011 with an annual growth of 7%. The GFRPs dominate this market.

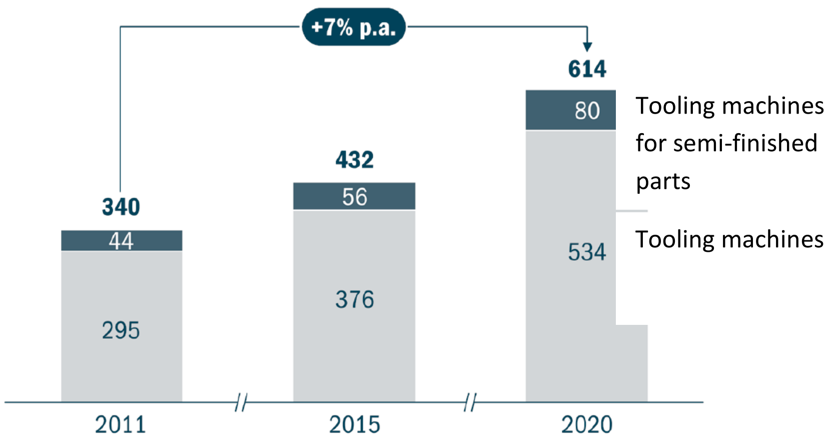


Figure 2: Global market of manufacturing systems for fiber reinforced polymers in Mio € [Study by Roland Berger: "Global market of manufacturing systems for fiber reinforced polymers"]. Taken into account are only at least partly automated processes.

The market figures given above take into account the whole market. The laser machine market figures are not available. ILT and its partners assume an annual laser machine market for polymers of 20 Mio € per year in Germany. The global market can be assumed to be twice as large, but only roughly 10% is spent for beam source. Therefore the polymer market is only a niche market.

Pumping of Fiber Lasers

Pumping of fiber lasers is not addressed in the DoW. Nevertheless the high brilliance 35 µm BRIDLE S5 modules (in combination with the fiber combiner under development at the ILT) will lead to new options for building efficient fiber lasers. The spatial overlap of the pump light and the active core can be increased by a factor of approximately 10. This will lead to shorter lengths of the active fiber, reducing the price for the active fiber and reducing losses due to Raman scattering.

With the newly developed BRIDLE-I1 modules, it is possible to increase the total power brought to the end of the active fiber significantly. The fiber laser design can be adapted to the higher pump power density with benefits for active fiber length, reduction of nonlinear effects and potentially higher efficiency.

It is expected that a growing part of the state of the art 200W, 200µm NA0,22 standard modules which are built in large quantities today will be replaced by the BRIDLE-I1 type modules. Most of the pump laser market for the higher power fiber lasers is dominated by a few large laser companies trying to meet their own (laser design driven) demands in-house. As far as Dilas alone is concerned, the intra-company transaction volume within the Rofin Sinar group with standard pump modules is about 10 M€ in the last year, and growing fast.

Newly designed fiber lasers in the lower power regime will also benefit from the higher brightness pump modules from BRIDLE and open new markets in the near future.

Glass frit bonding

Glass frit bonding (glass soldering) is not addressed in the DoW. The process can be used in order to encapsulate sensors or light emitting displays [EP 1811587 A2], e.g. screens of smart phones and large screen LCD-TVs. For small displays, i.e. for smart phones, laser based glass frit bonding is on the cusp of industrial relevance. Some manufacturers have just started to integrate glass frit bonding into their production. On the other hand laser wavelengths in the range of 500 nm up to 800 nm are much more adapted to the absorption spectrum of the commonly used frits. For efficient laser based glass frit bonding, laser powers in the range of 100 W up to a 300 W and fiber diameters of roughly 100 µm will be necessary. In this wavelength range, up to now, there are no cost efficient cw sources available. On the one hand diode lasers offer the possibility of a wide range of emission wavelengths. On the other hand wavelengths shorter than 808 nm suffer from sigificantly lower output power (for the same BPP). For instance, DILAS highest brilliance diode laser module at 793 nm has 32 W of output power ex 105 µm fiber. Based on the technologies developed in BRIDLE, 100 W of direct diode laser radiation out of a 105 µm fiber at emissions wavelengths in the 7xx range might be available in the near future. Hence the results obtained in the BRIDLE project can help today's diode laser companies to enter into the important display market.

Building Block for Future Laser Sources

At DILAS Diodenlaser, most of the fiber coupled direct diode laser sources and fiber laser pump modules are based on a 200W class standardized diode laser baseplate which is produced in large quantity (several hundred per week) in an automated production environment. This module is then used in standard products to scale the output power from the fiber into the multi-kilowatt power region with the help of well-known coupling schemes like polarization, spatial and coarse wavelength multiplexing

All the technologies developed in BRIDLE (especially based on the BRIDLE-I1 module and results from dense wavelength multiplexing) can and will be included immediately into this environment and serve as the fundamental new building block for future higher brightness laser sources.

Once a proof-of-concept for a high-brightness diode direct laser is demonstrated successfully, the technology can easily be adapted to new requirements.

Furthermore, an especially successful demonstration of coherent beam combining would open the door to new diode-laser concepts overcoming all current limitations regarding brightness.

Other High-Brightness Applications

The high-power single-mode laser diodes at IR wavelengths developed for the CBC are well suited for multiple other applications like pumps for fiber amplifiers, sensors and illumination in biophotonics. The pump laser market for EDFAs alone is about $100M market for laser components and the laser specifications set for BRIDLE CBC laser are well aligned with the state-of-the-art performance in this market. The high-brightness 9xx nm laser designs developed in Bridle can be easily transferred to other wavelengths between 750-1064nm, which opens up applications in industrial sensing, like Raman spectroscopy or gesture recognition. The industrial instrumentation market offers a component and sub-system market in the range of >$400M for a company like Modulight capable of delivering complete systems solutions based on lasers. The high-brightness single-mode lasers are extremely well suited also for frequency doubling opening potential for a very compact high-power lasers at visible wavelengths. Modulight already provides sub-system and turnkey system solutions to life science market (>$500M market), like fluorescence and is thus well positioned to offer this technology to to leading biophotonics systems integrators globally.

Summary of Applications

Application	**Power range**	**Fiber diameter**	**Relevant BRIDLE modules**
Cutting (metal sheet) global market	≥1kW	~100µm	kW class demonstrator
Welding (metal) global market	>1kW	≥100µm	kW class demonstrator
SLM and Additive Manufacturing	200W – 500W (50W – 2kW)	≤100µm	kW class demonstrator T-bar module DWDM module

Polishing	50W - 800W	≤100µm	kW class demonstrator T-bar module DWDM module
Polymer Welding and Cutting	1kW (GRP) 50W (micro-fluidics)	100µm - 400µm ≤35µm (micro-fluidics)	kW class demonstrator DWDM module
Pumping of Fiber Lasers DILAS only	200W 300-400W 600W- 1kW	200µm 0,22 100µm<0,15 200µm 0,22	kW class demonstrator
Pumping of Fiber Lasers global market	>100W (>25W)	≥100µm	T-bar module
Glass Frit Bonding	>100W	~100µm	T-bar module
Pumping EDFAs	<10W	single-mode	CBC demonstrator
Pumping of ultrafast lasers	50 W	≤35 µm	DWDM module

Table 1: Overview of applications, which can be addressed with BRIDLE developments. The market values are rough estimations and are derived from the above mentioned sources.

*) values for macro processing only – pumping applications in micro-processing (e.g. engraving & marking) and general solid state laser pumping could be in the same order of magnitude, but have different requirements (e.g. different wavelength) and is not investigated in this project

1.5 Dissemination and exploitation activities

During the project, all partners have been actively engaged in promoting the project and disseminating the results of their work. During the period M19-M42, there have been a number of key dissemination activities, which are discussed below. A more detailed description of these and indeed of all dissemination activities in Period 2 (M19-M42) can be found in D8.11.

- **Project website: www.bridle.eu**
  - The public project website has been regularly updated with new results, details of scientific publications, items to download (including e-Newsletters and tutorials) and most recently, a video clip demonstrating the cutting of sheet metal with a *BRIDLE* direct diode laser. The website has experienced regular traffic, with in excess of 6000 visitors since the start of the project and more than 1500 documents downloaded to date. More details can be found in D8.11.
- **e-Newsletters**
  - Four e-Newsletters were prepared and distributed during the project period. On each occasion, the distribution was to more than 550 people outside of the Consortium. All e-Newsletters are

available for download from the project website. Following the distribution of the 3rd and 4th e-Newsletters, D8.7 and D8.8, respectively, were completed and submitted.

- **Tutorials**
  - A series of tutorial presentations were published on the project website on key project technologies. These personations were adapted from tutorials given by partners at conference or when visiting partner institutions. The topics are listed briefly below and full details can be found in D8.11.
    - Tutorial on High Brilliance Diode Lasers (FBH)
    - Tutorial on External Cavity Laser Design (UNott)
    - Tutorial on Coherent Beam Combining Techniques (CNRS-IO)
    - Tutorial on Dense Wavelength Division Multiplexing (ILT)
- **Press release**
  - At the end beginning and at the end of the project, a project press release was prepared and distributed. The press releases were widely distributed to the scientific/technical press and are also available on the *BRIDLE* website. Full details can be found in D8.9.
- **Video clip**
  - At the end of the project, a short video clip was prepared by ILT showing sheet metal cutting using a direct diode source developed in *BRIDLE*. The video was uploaded to YouTube and is also available on the *BRIDLE* website. The video was also promoted in the final e-Newsletter. Full details can be found in D8.10.
- **Scientific publications**
  - The number of scientific publications (journal papers/conference presentations) from the project now stands at 54 (increased from 23 at M18). As testament to the quality of the work of the project, it is noted that 13 of these were invited papers/presentations. A full publication list can be found on the project website and also in D8.11. It is also worth noting that a number of publications are in progress and others will also result from the work of *BRIDLE* in the near future.
- **International conferences**
  - BRIDLE partners have been involved in many international conferences, not just as presenters, but also having involvement in organising and chairing sessions/events. Some notable examples are described below.
  -
    - At the 2014 International Semiconductor Laser Conference (ISLC), held in Palma de Mallorca, Spain, a Sunday Workshop took place on “Improving Brightness and Efficiency of High-Power Lasers”. *BRIDLE* member Paul Crump (FBH) co-chaired the workshop together with Gary Smith (MIT Lincoln Labs) and the *BRIDLE* Consortium presented two invited talks at the workshop.
    - Just as in 2013, the Consortium played a major role in supporting the *High Power Diode Lasers and Systems Conference (HPD ‘15)*, which was co-located with the *Photonex* exhibition held in Coventry, UK, in October 2015. The partners were active participants in the conference with many of the Consortium in attendance and 6 posters presenting results of the project. Partners also played a significant role in the program organisation with Eric Larkins of UNott chairing the conference and 3 other partners (Thomas Brand, Martin Traub, Paul Crump) being members of the *HPD ‘15* technical committee.