The BRIDLE project: Publishable Summary

(www.bridle.eu)

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

1.1 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.

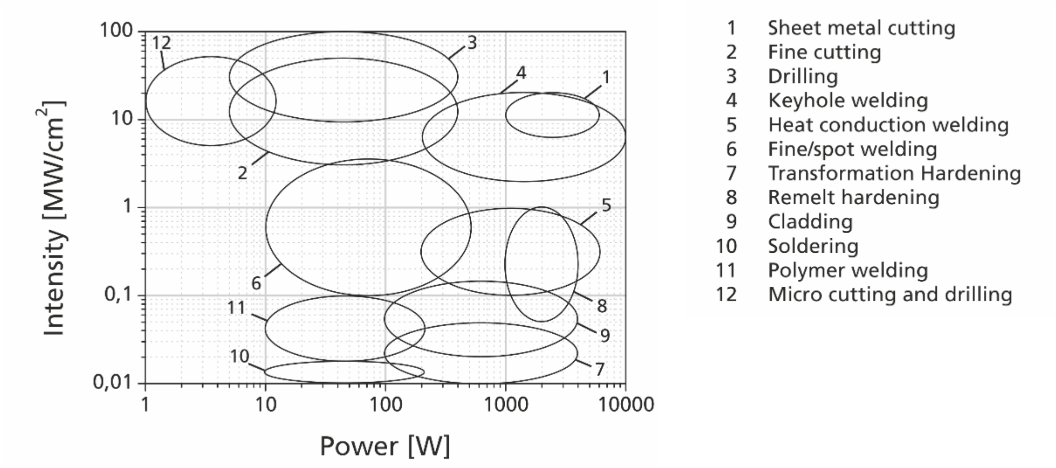

Fig. 1: Typical power and intensity requirements of high power laser applications.

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.

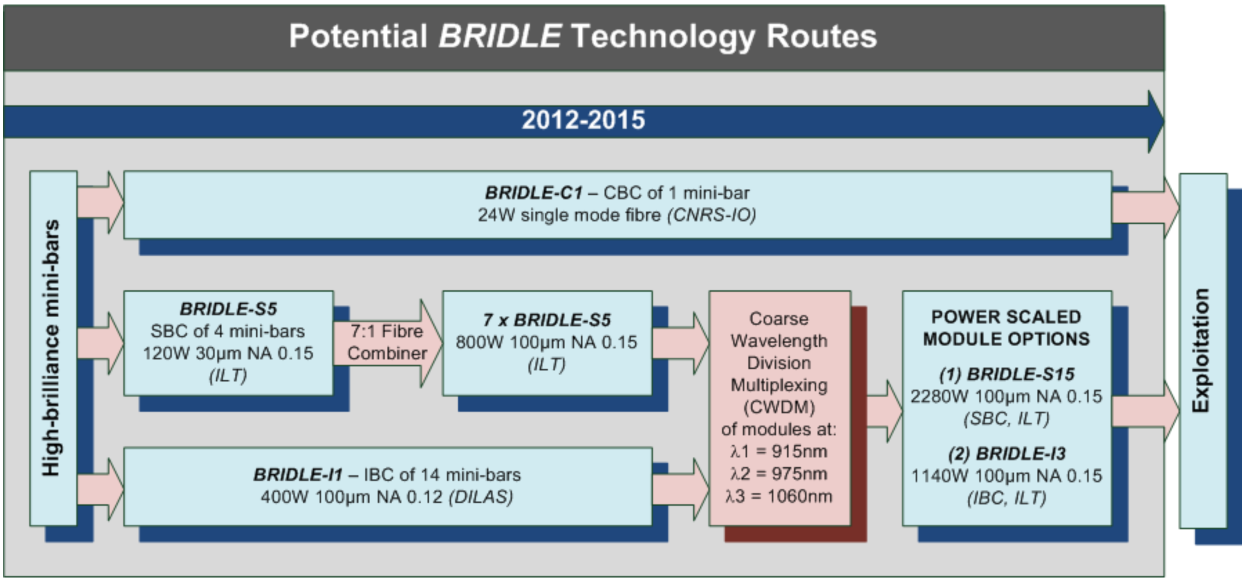

Fig. 2: BRIDLE's initial technology development approach.

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,	Mini bars with chirped grating manufactured and tested in lab environment, mini-bars were	1	5

internally stabilized	successfully integrated into fibre coupled prototypes		
High power, high lateral brightness diode laser bars	Brightness doubled compared to the state-of-the-art, demonstrated in relevant environment	4	6
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