Publishable Summary

Objectives

The BRIDLE project seeks to deliver a technological breakthrough in cost effective, high-brilliance diode lasers for industrial applications. By employing advanced high-power diode laser technologies and beam combination architectures, dramatic improvements in performance, cost, manufacturability and future scalability will be achieved. During the project, these technologies will be integrated into a sequence of increasingly high-brilliance demonstrators, each targeting specific industrial applications, leading up to an affordable diode laser source with an output power of >2kW from a Φ100µm optical fibre and efficiency >40% suited for sheet metal cutting.

BRIDLE's approach is modular, scalable and forward compatible. It begins with high brilliance mini-bars with 2-3x higher brilliance (~7W @ 0.8-1.5mm.mrad) than the best broad-area emitters (~7W @ 2.7mm.mrad). Based on these diode laser bars, different scaling concepts will be evaluated: spatial multiplexing based on optical stacking of 7 mini bars in the FA is chosen for the BRDLE IBC (incoherent beam combining) approach. Spectral beam combining (SBC) allows a further increase of the total brilliance by 30-40x. Advanced coherent beam combining techniques are also being pursued to develop phase-coupled mini-bars with a nearly diffraction limited output to facilitate further significant improvements in both spatial and spectral brilliance. The IBC and SBC approaches are investigated in parallel, resulting in a high level of risk mitigation as the final system can be set up by using IBC and SBC modules. The concept of power scaling is shown in figure 1.

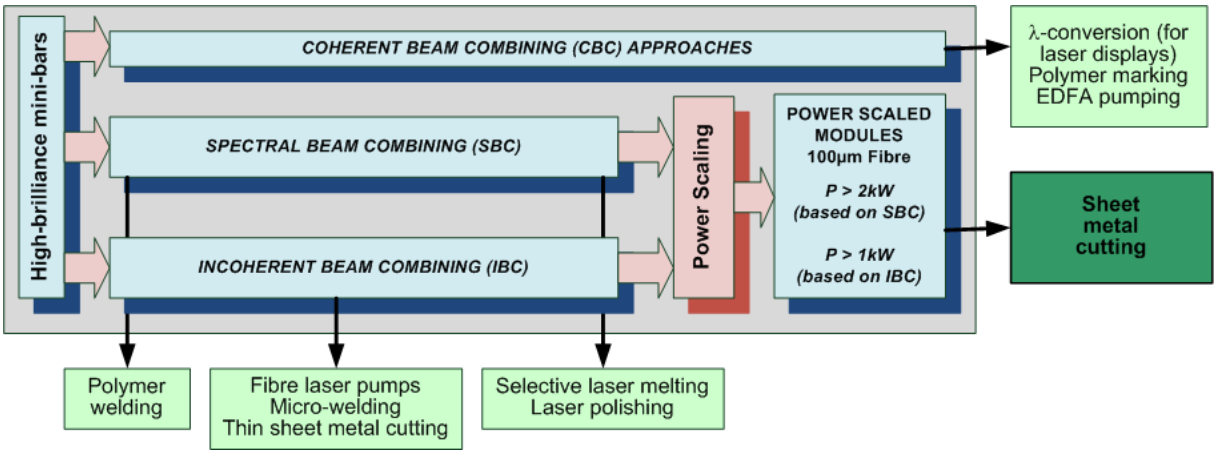

Figure 1: The modular approach of BRIDLE and typical applications to which BRIDLE laser modules will be suited.

BRIDLE's approach is chosen to be compatible with manufacturability and cost scaling requirements. State-of-the-art simulation tools are being used to optimise designs for laser bars and systems. The cost and complexity of the optical system are reduced by integrating optics inside the mini-bars. Efficient, extremely low vertical divergence structures will lead to low-cost, smile-insensitive assembly and low-loss optical coupling. The chosen packaging and beam combining techniques will allow simple fabrication and good thermal management.

Performed Work

In the first 18 months, the following activities have been carried out:

- Design, manufacturing and test of ridge waveguide diode lasers, tapered lasers, and broad area diode lasers (both single emitters and mini bars)
- Evaluation of different approaches for external chirped spectral stabilization and multiplexing, comparison with internally stabilized diode laser bars

- Optical design of the SBC building block
- Design of diffractive optical elements for coherent combining
- Coherent superposition of two tapered lasers in Michelson configuration
- Coupling of laser simulation tool (SPECLASE) with commercial optical modelling software (ZEMAX), Design optimisation of high-power laser diodes for operation in external cavity
- Realisation of a 7:1, 35 µm/105 µm integrated fiber-to-fiber combiner
- Experimentally demonstrated to couple 7 newly developed NBA mini bars into a 105 µm fibre with an optical output power of 120 W (without employing polarization multiplexing)

Main results and expected results

WP2: Bar fabrication

Device design, epitaxial growth, wafer processing, facet passivation, packaging and test of broad area diode lasers have been completed on a second design iteration. The work focused on one vertical structure and one resonator length, and several design changes were included, e.g. the grating order of the internally stabilized lasers were optimized to eliminate second Bragg peaks in the spectrum. Current results are shown in figure 2.

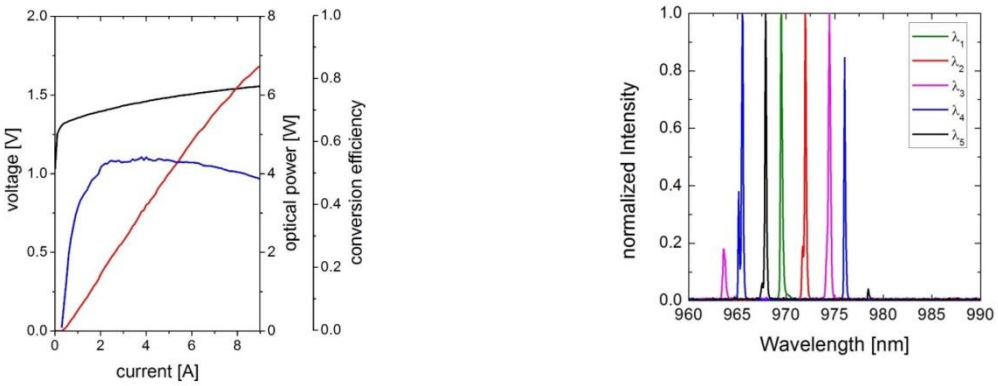

Figure 2: Power-voltage-current characteristics of an 80th order surface-etched DFB laser with a length of 6mm and a stripe width of 30µm (left); spectra of 5 single DFB lasers with a 28nm spacing of the grating periods (right).

Both tapered and broad area single emitters were coupled in a 35 µm fiber. The results gained with BA lasers were significantly better, thus FBH will focus on optimizing BA lasers in the BRIDLE project. As the diode laser bars available after 18 months did not meet the performance targets, the consortium agreed on the following revised work plan: FBH will focus on the 975 nm wavelength range for stabilized broad area diode lasers and free running diode lasers at 940 nm, 975 nm and 1060 nm. To optimize the diode lasers, two additional iterations have been added to the work plan with a final performance target of P = 7W per emitter and BPP < 1.5mm-mrad.

Ridge waveguide diode lasers which will be used for coherent beam combining have been designed and processed by Modulight. An output power of more than 1000 mW has been demonstrated with single RW diode lasers. RW diode laser bars have been fabricated by Modulight and are currently packaged by DILAS and ILT.

WP 3: Spectrally beam combined emitters and bars

In WP3 five different configurations for the external stabilization have been analysed. It was shown that none of these configurations is suited for the goals of the BRIDLE project. A fundamental understanding of cross talk between the emitters on one bar has been obtained.

Spectral multiplexing based on external stabilized bars was not performed, as the diodes of the first run failed early and as the internal stabilization seems to be most promising. This procedure follows the recommendations from the BRIDLE project review in July 2013.

The optics design for the BRIDLE S5 sub-modules is finalized after being adapted to the new characteristics of the diodes and the mechanical design is being developed. The multiplexing efficiency with VBGs and dielectric filters was calculated for externally and internally stabilized diodes. Based on these calculations the specifications were finalized for VBGs and for dielectric filters in strong collaboration with three different manufacturers. First ultrasteep dielectric filters were sourced and characterized (see figure 3). Based on the filter design tested, filters for all wavelengths will be sourced and used for the next SBC experiments and for the final SBC module.

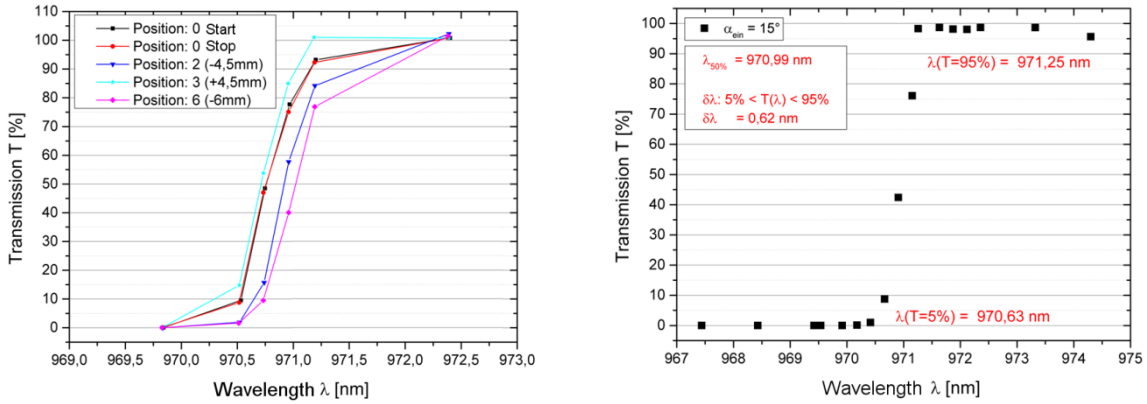

Figure 3: Homogeneity (left) and edge steepness (right) of an ultra steep dielectric filter.

WP 4: Coherent beam combining approaches

For the combination of N beams into one, diffractive optical elements (DOE) have been designed. The gratings will be used to couple five emitters with equal power. In the first 18 months, different grating designs based on binary, multistep or continuous phase profile have been compared. For the design of the transmission phase gratings, a numerical software tool has been developed.

First experiments with two tapered lasers in a passive Michelson cavity have demonstrated the partial phase-locking of the two lasers, resulting in a combining efficiency of about 75% (figure 4 left). The glass plate enforces the coherent operation of the two lasers, with constructive interference on the beamsplitter. Tapered-laser mini bars have been packaged and will be used for CBC experiments in the next months (figure 4 right).

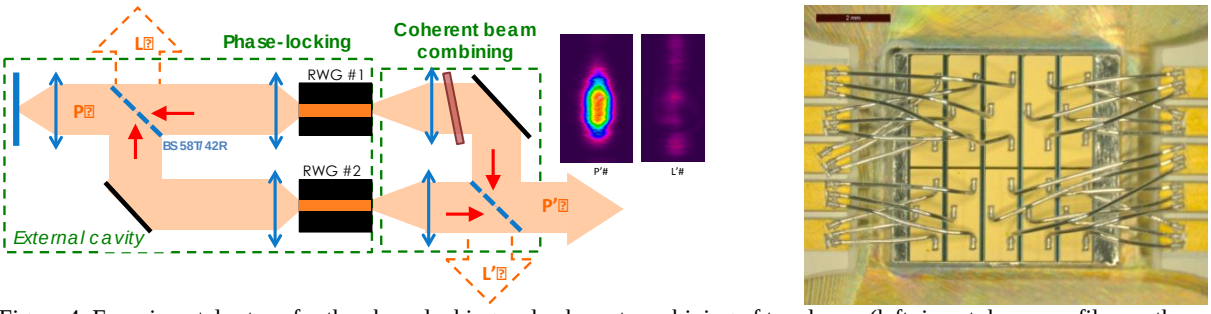

Figure 4: Experimental set-up for the phase-locking and coherent combining of two lasers (left; insert: beam profiles on the output P' and L'); individually addressable tapered mini bar (right).

WP 5: External Cavity Laser Simulation

Significant effort in the recent period was devoted to the assessment of devices fabricated by Modulight, which were based on initial designs from UNott. The results of this analysis were then used to guide further design work. Devices with high mirror loss (short cavity and/or low facet reflectivities) require a large modal gain, which the SQW struggles to deliver. Consequently, UNott has focused on the use of a DQW gain medium for the next designs, whose composition has been modified to shift the emission wavelength to the target value. Considerable effort was also devoted to increase the PCE of the devices.

For the FBH devices, calculations were performed to optimize the ELoD2 design. The work in this period focussed initially on designing narrower waveguide epitaxial structures and subsequently simulating tapered lasers based on these narrow waveguide designs.

UNott has continued to develop a model to bi-directionally couple its laser simulation tools to *ZEMAX*. Currently, the model is capable of converting a near- and far-field distribution into a ray distribution which *ZEMAX* can then propagate and trace through arbitrarily defined external optics.

WP 6: System Design and Integration

As this work package depends on the availability of the diode laser bars, the main effort will be spent in the second half of the BRIDLE project. A first iteration of the 7:1 fiber combiner has been finalized and characterized. Both tapered and broad area diode lasers have been coupled into a 35 µm fiber, and the coupling efficiency of the BA lasers amounts to 85% for an uncoated fiber.

At DILAS, a first T-bar platform based module was set up, delivering 120 W out of a 100 µm fiber without polarization multiplexing. Further improvements will be achieved by adapting the microoptics to the far field of the broad area diode laser bars.

Depending on the performance of the IBC and SBC modules, the final system will be built up using either spectrally combined modules, incoherently combined modules or a mixture of both.

WP 7: Evaluation of laser systems and modules

The work in work package 7 will start as soon as the laser source is available.

Dissemination

Two Newsletters have been published, and the 2nd e-Newsletter was recently distributed to more than 550 people outside of the Consortium. In the first 18 months, 23 scientific papers have been published. The Consortium played a major role in supporting the *High Power Diode Lasers and Systems Conference (IEEE HPD '13)* by giving 4 of the 9 invited talks and 4 of the 12 contributed poster papers.

Further information can be found on the BRIDLE webpage (www.bridle.eu).