1 kW cw fiber-coupled diode laser with enhanced brightness

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ABSTRACT

We developed a 1kW cw fiber-coupled diode laser at 9XX nm by using beam combining of eight high power diode laser bars. To achieve beam combining, we employ Lyot-filtered optical reinjection from an external cavity, which forces lasing of the individual diode laser bars on intertwined frequency combs with overlapping envelopes and enables a high optical coupling efficiency. Unlike other spectral beam combining techniques that are based on the use of grating elements, this technique is insensitive to the thermal drift of the laser diodes. In addition to this, the FWHM spectral width at 1 kW output power is only around 7 nm, which is convenient for wavelength sensitive applications such as pumping.

Keywords: fiber coupled diode-laser, high-power, high-brightness, Lyot filter

1. INTRODUCTION

During the last years, continuous development of high-power broad-area edge-emitting semiconductor lasers has resulted in an unprecedented high optical output power of GaAs-based single emitters and emitter arrays. While the optical output power of a single emitter can reach up to 30 W[1], the output power of a 10 mm width laser bar can exceed 1.6 kW and 500 W in continuous wave operation (CW) when using cooling temperatures of -55ºC[2] and 15 ºC[3], respectively. Moreover, rapid development of efficient semiconductor lasers has also occurred recently in the blue region of the spectrum. Laser bars with an output power of 50 W have been shown, which can be combined to achieve a 700 W fiber-coupled blue laser that can be used for processing materials with low absorption in the near-infrared (NIR)[4].

This type of lasers has reached a wide variety of applications such as end-pumping of fiber lasers, sheet metal welding and additive manufacturing, among other applications. While semiconductor lasers in the NIR are the most efficient light source in the market, their still relatively low power and low brightness require suitable beam combining techniques that allow reaching high-brilliance emission and output powers in the kW regime. Side-by-side beam combining schemes, while they enable a power scalability, they lack brightness scalability[5]. This disadvantage can be circumvented by spectral beam combining where beams at different narrow, non-overlapping wavelength windows, are combined into a single beam by using various diffractive optical elements[6]. There are several disadvantages to these schemes, however. On the one hand, in order to increase the power, more beams need to be coupled, increasing not only the beam spectrum but the requirement of unconventional laser wavelengths. On the other hand, spectral beam combining efficiency is often affected by possible thermal drifts of the central wavelength of the individual lasers. Polarization beam coupling can increase the brightness, maintaining the spectral width and is robust against thermal drifts, however, the coupling can only be performed once.

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Table 1. Comparison between RPC and conventional beam combining schemes.

Advantage \ Beam combining schemes	Side-by-side	Spectral	Polarization	RPC
Brightness increase		X	X	X
Spectral width maintenance	X		X	X
Thermal drift robustness	X		X	X
Cascadable concept	X	X		X

We have developed a 1 kW diode laser fiber-coupled module by using a polarization and spectral beam combining technique that we named rectified polarization coupling (RPC). In this technique, beam combining is achieved by Lyot-filtered optical reinjection, in which, multiple laser beams, with the same wavelength and polarization, are combined with a high coupling efficiency. RPC offers some advantages as opposed to the other beam combining techniques: it is insensitive to thermal drifts of the individual emitters, it produces efficient brightness increase, spectral width is not much more than the spectral width of an individual laser source, and the concept is cascadable, which allows combining multiple laser sources. Table 1 shows the advantages of RPC as opposed to all the other conventional combining techniques[7].

In this study, we report the development of a 1kW cw fiber-coupled diode-laser module at 9XX nm. In the next chapter we explain in detail the RPC technique. Next, we present the 1kW cw fiber-coupled diode laser starting by examining the basic building blocks and finishing by analyzing the overall module performance. Finally, we discuss further improvements that can be applied and present our conclusions about the module development.

2. RECTIFIED POLARIZATION COUPLING

The beam combining scheme of the emitters is based on a common external cavity which contains a Lyot-filter and provides an individually filtered optical reinjection to each emitter. As we will explain in the following, the filtered optical reinjection leads to a self-adjustment of the spectral output of the emitters to intertwined frequency combs with overlapping envelopes, which enables a high optical coupling efficiency.

Figure 1 shows a schematic of the assembly for coupling of two laser bars. The setup consists of two identical high-power diode lasers with collimation optics, a half-wave plate (HWP), a Lyot-filter and a partially reflective mirror (R = 4%). The Lyot filter consists of two polarization beam splitters (PBS) with a birefringent crystal (BC) in between. The optical axis of the BC should be aligned under an inclination of 45º with respect to the polarization of the two beams. To swap between the horizontally and vertically polarized field components of the LD 2, a (zero-order) HWP is placed after the collimating optics.

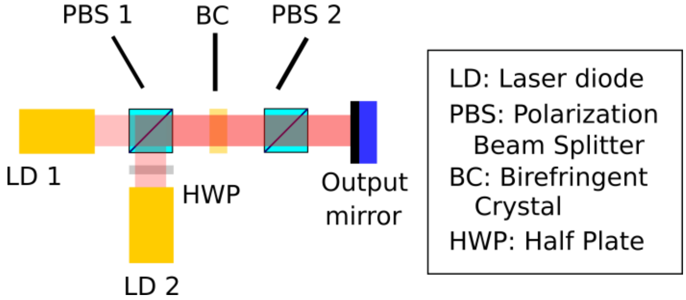

Figure 1. Schematic diagram of the rectified polarization coupling (RPC) technique for two diodes.

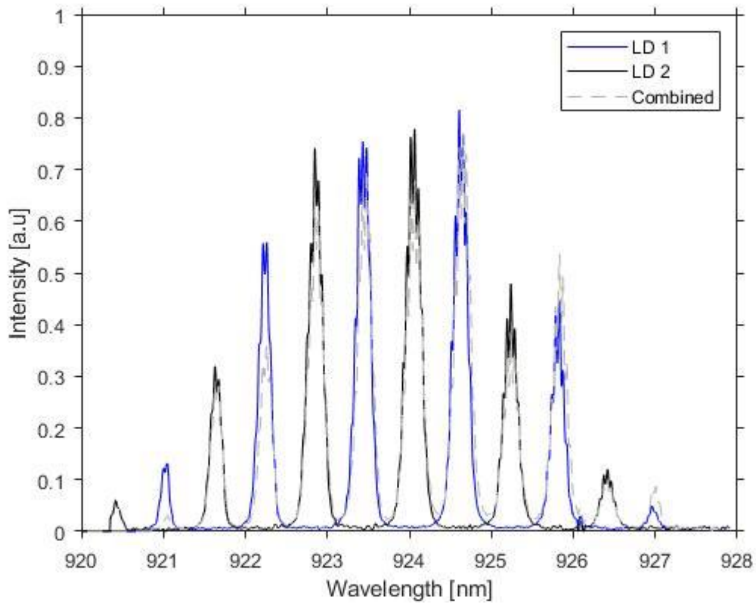

Figure 2. Experimental spectrum of two lasers combined by RPC.

The first element of the setup (PBS 1) accomplishes a regular polarization beam combining of LD 1 and LD 2. During its transmission through the dispersive BC, the two combined beams undergo a wavelength-dependent change of polarization state. The BC acts as a HWP for a set of wavelengths λs, located at the maximums of LD 2 curve in Figure 2, and as a phase neutral for the other λc , located at the maximums of LD 1 curve in Figure 2, being λc shifted half period with respect to λs. For LD 1, only λc is let through the PBS2 and can partly be reflected by the semitransparent mirror. The reflected light can again pass the PBS2, pass the BC again as a phase neutral, allowing giving feedback to LD 1 after passing PBS 1. Similarly, for LD 2 λs, which is the other frequency comb, is transmitted through the PBS 2, and part of the light is reflected by the mirror. After it is reflected can again pass PBS 2, then it is rotated 90º by the BC, and redirected in the PBS1 back to LD 2. For both sources a self-amplifying feedback loop is closed, which leads to an oscillation on exactly those wavelengths that match best the respective filter characteristics and thus have the least losses per round trip.

Figure 2 shows the output spectrum of the combined LD 1 and LD 2 as dashed grey curve, whereas the independent spectra of both diodes are shown in blue and black color. Both spectrum combs are perfectly intertwined, and the amplitude of the peaks is determined by the characteristics of the-Lyot filter. What is more important is that the output beam has the same beam diameter and divergence as the original laser sources, and polarization is still linear, which allows to combine this beam with another orthogonally polarized.

Due to the periodicity of the filtering function this assembly is insensitive to thermal drifts of the central emission wavelength. Instead of increasingly cutting the efficiency of the lasing line, which comprises a typical drawback in spectral beam combining schemes, the laser line can “evade” by changing laser oscillation to a neighboring laser line predefined by the filter. The fact that spectral multiplexing becomes possible for intertwined wavelengths allows development of high-power pumping sources. As for this aspect it is important, that the periodicity is smaller than the locking region of the laser because then the filter does not need to be exactly adapted[7].

A further benefit of this technique is that as opposed to coherent coupling this kind of multiplexing is tolerant against failure of single gain elements. As all single gain elements oscillate independently and on separate wavelengths the failure of a single element does not influence the other lasers.

This procedure can be cascaded by multi-step filter that has to be passed sequentially by the light. Meaning that the number of combined beams can be cascaded in powers of two.

3. 1 KW DIODE LASER MODULE DESIGN

3.1 Packaging of NIR diode laser bars

Today, commercial diode laser bars are typically mounted using a soldering process. We can differentiate two main techniques depending on the type of solder composite that is used: soft soldering and hard soldering. Figure 5 a) and b) shows a schematic view of the heatsink assembly.

In a soft soldering process the laser bar is directly attached to the copper heatsink. Given the significant difference between the coefficient of thermal expansion (CTE) between the laser bar and copper (6.8 ppm/K for the GaAs-based semiconductor and 17 ppm/K for the copper), a ductile and malleable soldering composite such as indium is needed to absorb the mechanical tensions that appear in the cool-down phase. Bonding with indium solder has the disadvantage that it suffers from thermal fatigue and thermo-electro-migration, especially when the laser bar is operated in pulse regime, resulting in failing of the device in time.

Hard soldering is used to improve the reliability of the device. The laser bar is attached to a CTE-matched submount such as diamond, ceramic or tungsten-copper composites, using gold-tin solder. In a second step, the package of laser bar and submount is mounted on the copper heatsink by soldering with a composite with lower melting temperature than gold-tin. The gold-tin joint does not easily degrade during thermal-mechanical cycles, which improves the reliability of the device. However, adding an additional submount with a lower thermal coefficient than copper and an intermediate soldering layer adds an additional thermal resistance between the semiconductor and the heatsink[8].

Moreover, the induced thermal-mechanical stress causes the curvature of the laser bar, or the so-called “smile” phenomenon. This curvature can reach values peak to valley as high as 5 µm, but typical values are in the range of 1 µm when using indium soldering. As a consequence, the smile can reduce the beam quality when using optics by a factor of 2 [9].

Monocrom uses its proprietary patented solder-free mounting process (*Clamping*^{TM}) that overcomes most of the problems of the solder-based techniques[10]. The laser bar is clamped between the two copper heatsinks by applying uniform pressure over the bar contact surface (see Figure 3 c))[11]. Since the mounting process takes place at room temperature, mounting induced stress by CTE-mismatch is avoided. The laser bar can still expand between the electrodes when heating up avoiding thermal-mechanical induce fatigue during operation, which increases the lifetime of the device. In addition to this, elimination of the intermediate layers reduces the thermal resistance between the heatsink and the semiconductor, affected by the homogeneity of the contact. Moreover, since the laser bar is contacted from both sides, cooling takes place also from the n-side (around 20% of the heat is removed from the n-side contact), reducing the thermal load in the p-side.

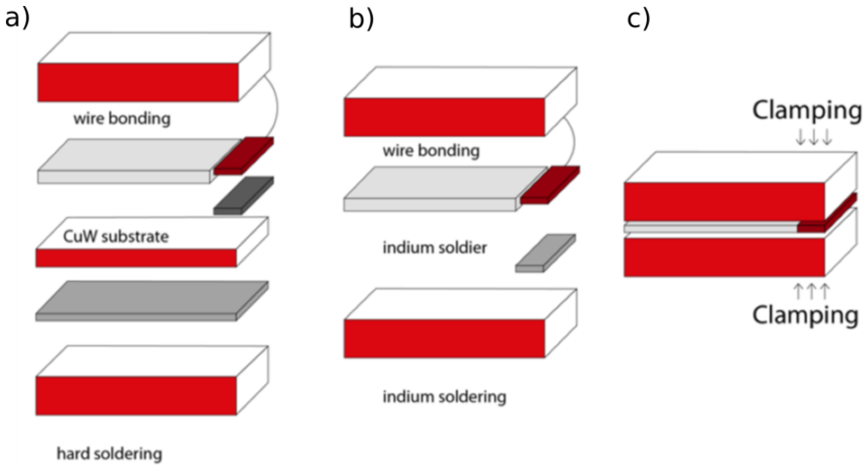

Figure 3. Schematic view for laser bar mounting with a) hard soldering with gold-tin, b) soft soldering with indium, and c) *Clamping*^{TM}.

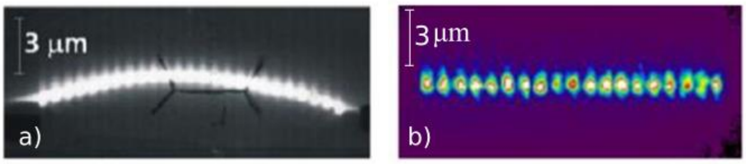

Figure 4. a) Enlarged picture of a soldered diode laser bar with a 'smile' of approx. 2 µm. Image taken from Ref. 8. b) Enlarged picture of a diode laser bar mounted with *Clamping™*, showing a smile under 0,1 µm.

Another important benefit offered by this technology is the very low smile achieved. Figure 4 b) shows a magnified image of the emitters of a clamped bar with a peak-to-valley value of ~0.1 µm. Typical values of smile <0.3 µm are systematically achieved by clamping.

3.2 Single diode laser bar module

All the kW fiber coupled diode laser modules own most of their specific characteristics due to the individual laser sources that they combine, their building blocks. Wisely choosing this building blocks shall pave the way to a successful kW diode laser development.

The building block of the 1 kW diode laser module is a, 200 W, single diode laser bar module. The mounted diode laser bar has 23 emitters, with a 50 % fill factor that radiate at a wavelength of 9XX nm. The bar is mounted on an active heatsink with the two electrodes cooled (p and n electrodes). Micro-channel coolers typically suffer from clogging of the channels and electro-corrosion induced leakage, which leads to failing of the device[8]. To avoid clogging of the channels and to reduce the impact of corrosion, we use macro-channel coolers. In addition to this, as it is mentioned before, our *Clamping™* technology allows cooling of the laser bar from both sides, which ensures a low thermal resistance for the 4 mm resonator length laser bar of 0.3 K/W.

In Figure 5 the behavior of a single diode laser bar module, emitting at 976 µm, can be seen. At 200 A the diode laser bar module delivers 200 W at a power conversion efficiency of 67%, showing the ability of the mounting to remove ≈ 100 W produced as heat by the laser diode bar.

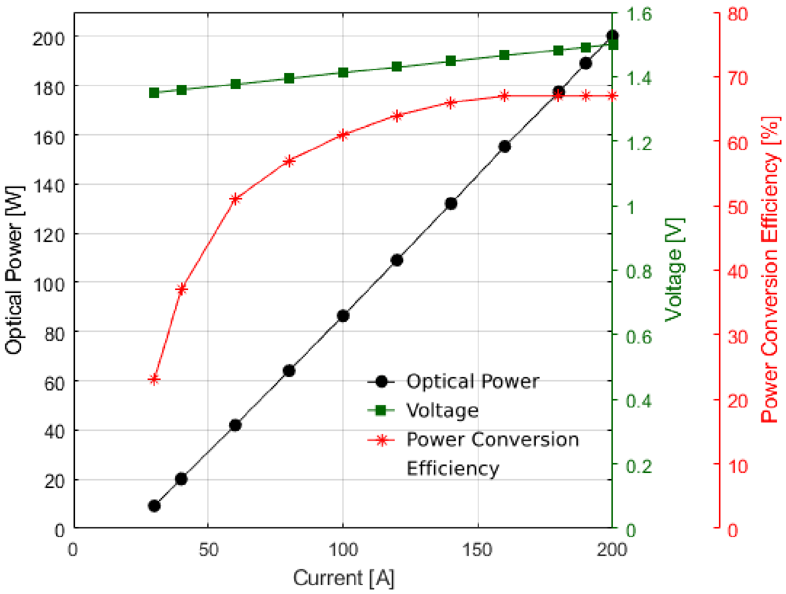

Figure 5. Dependence on driving current of optical power, voltage and power conversion efficiency of the single diode laser bar module (diode laser bar mounted using *Clamping™*).

3.3 Optical design

A challenging fact when designing a fiber coupling system for a broad area diode laser is managing the asymmetry shown by the emission. While in the fast axis, the axis perpendicular to the p-n junction plane, the emission shows a high divergence (23 º FWHM) and a relatively good beam quality ($M^2 = 1$), in the slow axis, the axis perpendicular to the fast axis and to the light axis, the emission shows a smaller divergence (6 º FWHM) but a much worse beam quality ($M^2 =$ 20-100)[12].In addition to the asymmetry of the emission, a diode laser bar is an array of broad area diode lasers arranged along the slow axis. This fact limits the focal lengths of the slow axis collimator (SAC), as it should be placed before the overlapping of the emission of two consecutively arranged emitters, due to the natural divergence in the slow axis. This limitation imposes SAC with short focal lengths and therefore with high residual divergence, around the tenths of mm·mrad, which, when focused, will turn into a large focusing beam spot.

To manage this constraint the optical solution chosen is based on beam transformation system (BTS), an industry standard solution for diode laser bars. The BTS is an extremely compact set of micro lenses that contains two elements: i) a fast axis collimator (FAC), with effective focal lengths below de the half millimeter, and ii) a biconvex cylindrical lens array, each one with an infinite effective focal length, tilted 45º, preforming a 90º twist[13]. The number of elements in the array matches the number of emitters in the diode laser bar. The twist purpose is to avoid the overlapping of the light from different emitters. Avoiding this overlapping enables the use of a common SAC for all the emitters in the laser diode, with a larger focal length, reducing the residual divergence.

After the BTS and SAC the beam is collimated and can be coupled according to the above-described RPC. The optical components are not shown in Figure 6 and are located where the bracket is shown. The lenses responsible to fiber couple the beam are two crossed cylindrical lenses, as it can be seen in Figure 6. The focal length of the cylindrical lenses is optimized to fulfill three conditions: i) achieve the minimum beam spot at the fiber facet, ii) not exceed the fiber N.A. and iii) respect the mechanical limitations imposed by the fiber input port characteristics. Conditions i) and ii) share a well-known compromise between each other.

Regarding the beam divergence, in order to match it with the fiber N.A. it is important to consider that the maximum angle occurs at the "corners" of the beam[14]. One of the bottom corners is represented in Figure 6 by a thick red line. The maximum angle of incidence on the fiber facet has a contribution of the two cylindrical lenses focal lengths.

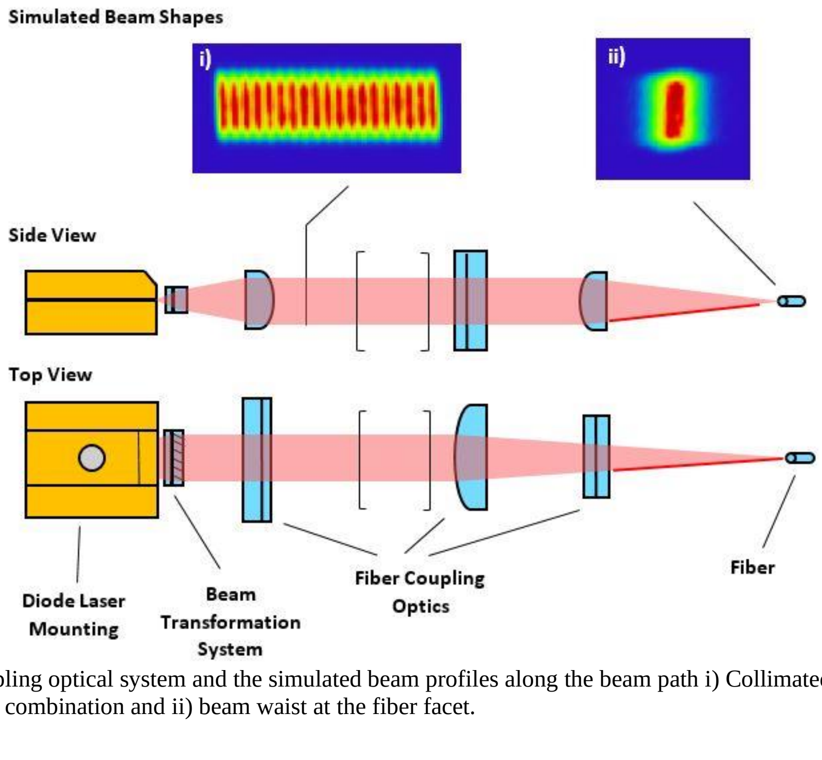

Figure 6. Fiber coupling optical system and the simulated beam profiles along the beam path i) Collimated beam profile after the BTS+SAC combination and ii) beam waist at the fiber facet.

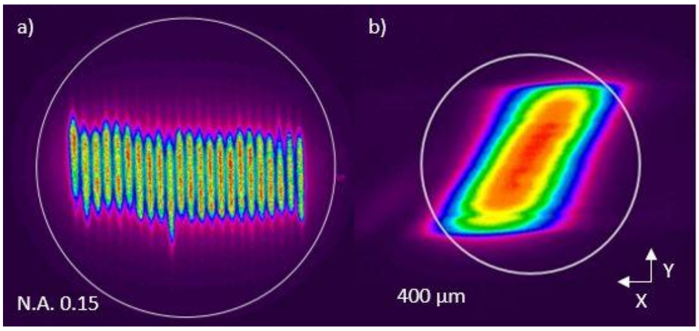

Figure 7. a) Focused beam far field. The circle represents a numerical aperture of 0.15. b) Magnified image of the focused beam at the fiber face. The circle has a diameter of 400 µm.

Finally, the last condition refers to the fact that the high-power fiber has an end-cap. This element is a cylindrical fused silica block, attached to one end to the fiber, and at the other end has an antireflective coating to avoid back reflections that would result in a loss of power. The coating cannot be placed directly at the facet of the fiber due to the high-density power. The end cap has a length of 22 mm, forcing the lens prior to the fiber to have a higher focal length.

In Figure 7, the final coupling conditions can be seen. These conditions give a fiber coupling efficiency exceeding the 90 % for a fiber of 400 µm core diameter and an N.A. of 0.22. The characteristics of the fiber are completed by an actively cooled mode stripper and a conical interface (QB standard).

3.4 1 kW laser system

The 1 kW cw fiber coupled diode laser module, shown in Figure 8, has been designed to be able to work in an industrial environment. The laser is sealed to protect the laser diode bars and the optics from humidity, dust and possible debris. These conditions are typical in application like cladding, heat treating and brazing. The enclosure is designed to fit in a standard 19-inch rack to enable an easy integration in larger systems. This module is an economic solution with an overall optical coupling efficiency of 64 % that lowers the price of operation.

Thanks to the *Clamping*^{TM} technology the eight diode laser bars show a longer life expectancy. The spectral FWHM is 7 nm, allowing several further spectral beam combining or using the laser module for pumping applications. The robust fiber cable allows an easy integration for the end-user. A variety of sensors and complements can be added to the module enabling monitoring the module behavior.

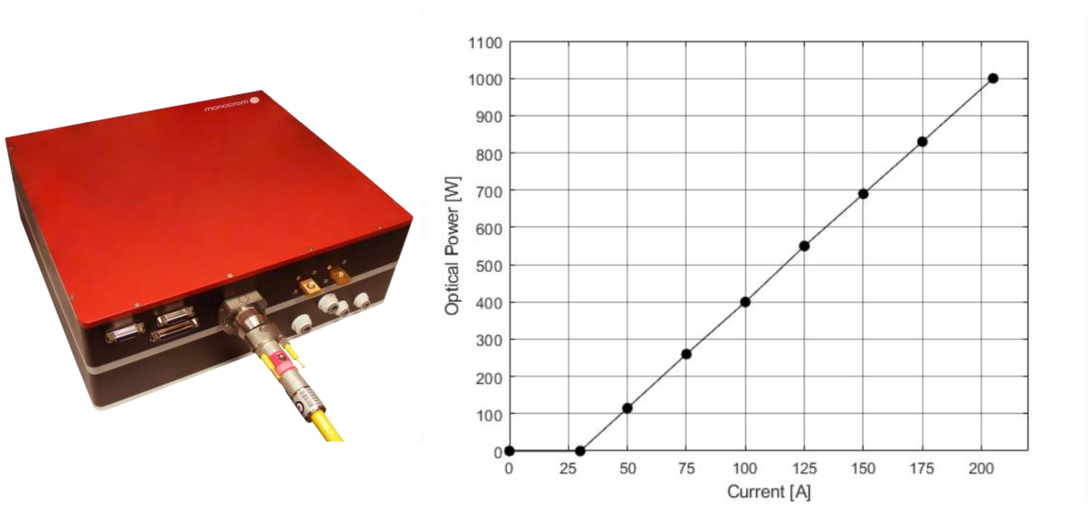

Figure 8. Monocrom 1 kW cw fiber-coupled module (left) and the corresponding power vs current diagram (right).

3.5 Future perspectives

The 1 kW cw fiber coupled diode laser module represents a first step towards a whole variety of multikilowatt diode laser modules for Monocrom. This variety of laser modules will be based on the module presented here, however, higher power can be reached by using side-by-side and spectral beam combining.

Moreover, in parallel to the work presented in this manuscript, we have developed a new technique for improving the beam spatial quality of the individual diode lasers and, correspondingly, increase in the brightness. This technique is based on the use of extremely compact photonic crystal (PhC) spatial filters, that incorporated in the laser resonator can induce losses to the transversal lasing modes with higher divergence[15,16]. We reported an increase in the brightness by a factor of 1.5 in a broad area diode laser as a the prove of concept. Incorporating the PhC spatial filtering in our system can improve the beam quality and reduce the diameter of the fiber core. This technique has been developed in parallel to the RPC, in the work frame of the HIP-Laser project.

Developing laser modules with higher spectral brightness is also possible by combining the RPC technique with the use of different diffractive optics placed inside the external cavity. This configuration is interesting for those applications that need high power confined in a narrow spectral window.

4. CONCLUSIONS

We have developed an optical coupling technique, RPC, that is able to combine multiple beams with the same wavelength and polarization. This coupling scheme shows several advantages compared to other conventional coupling schemes. Unlike side-by-side beam combining, RPC produces an effective brightness increase. In addition to this, RPC is insensitive to thermal drifts of the central wavelength emission, as opposed to other conventional spectral beam combining methods based on the use of gratings. Moreover, spectral beam combining increases the spectral width of the output beam, whereas RPC maintains the spectral width of the original laser sources. Finally, unlike coherent beam combining, RPC is tolerant against failure of a single element.

We have developed a 1 kW cw fiber coupled laser module based on the concept of RPC. This module uses eight laser diode bars, which are mounted in individual heatsinks using the *Clamping™* technology. The emission of each bar is then collimated using a BTS and a SAC. Once the beam is collimated the beams are combined by the RPC technique and finally coupled into a fiber with a 400 µm core diameter and 0.22 N.A.

AKNOWLEDGEMNT

This work is supported by the Eurostars Project E!10524 HIP-Lasers.

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