Novel high-brightness fiber coupled diode laser device

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ABSTRACT

High brightness becomes more and more important in diode laser applications for fiber laser pumping and materials processing. For OEM customers fiber coupled devices have great advantages over direct beam modules: the fiber exit is a standardized interface, beam guiding is easy with nearly unlimited flexibility. In addition to the transport function the fiber serves as homogenizer: the beam profile of the laser radiation emitted from a fiber is symmetrical with highly repeatable beam quality and pointing stability.

However, efficient fiber coupling requires an adaption of the slow-axis beam quality to the fiber requirements. Diode laser systems based on standard 10mm bars usually employ beam transformation systems to rearrange the highly asymmetrical beam of the laser bar or laser stack. These beam transformation systems (prism arrays, lens arrays, fiber bundles etc.) are expensive and become inefficient with increasing complexity. This is especially true for high power devices with small fiber diameters. On the other hand, systems based on single emitters are claimed to have good potential in cost reduction. Brightness of the inevitable fiber bundles, though, is limited due to inherent fill-factor losses.

At DILAS a novel diode laser device has been developed combining the advantages of diode bars and single emitters: high brightness at high reliability with single emitter cost structure. Heart of the device is a specially tailored laser bar (T-Bar), which epitaxial and lateral structure was designed such that only standard fast- and slow-axis collimator lenses are required to couple the beam into a 200µm fiber. Up to 30 of these T-Bars of one wavelength can be combined to reach a total of > 500W ex fiber in the first step. Going to a power level of today’s single emitter diodes even 1kW ex 200µm fiber can be expected.

Keywords: High power diode laser, fiber coupling, high brightness, beam quality, fiber laser

1. INTRODUCTION

Continuous improvement on chip level and the use of sophisticated micro-optics allow fiber coupled high power diode lasers (HPDL) to already compete with lamp pumped solid state lasers (LPSSL) in power and brightness. It will not be long until LPSSL are replaced by diode lasers in many applications.

While recently the development of diode lasers was driven mainly by increasing demands in materials processing, the introduction of fiber lasers as a preferred laser source in many applications have given the desire for higher brightness of fiber coupled pump modules a new boost. Eventually, this trend can be described by a simple equation: high brightness of the pump source leads to high brightness of the signal beam of the fiber laser. The required beam quality of the pump source is directly related to the design of the fiber laser i.e. the arrangement of pump fiber and gain fiber. Currently, two basic arrangements are used for most fiber laser designs:

- *End-pumped or dual end-pumped configuration*
    a) The pump beam is coupled via free space optics into one or both ends of a double-clad fiber, the high power signal beam has to be extracted by means of dichroitic mirrors (Fig. 1a).
    b) The pump beam is coupled via single-mode / multi-mode fiber combiner (typically 6+1 x 1) into a double-clad fiber.

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- *Side-coupled configuration*
  a) One or more multimode pump fibers are in contact with the active fiber within a common cladding [1].
  b) Distributed side coupling: many fiber coupled single-emitter modules (or lately dual/tripple-emitter modules) are attached (typically spliced) to the pump core of the active fiber (Fig. 1b).

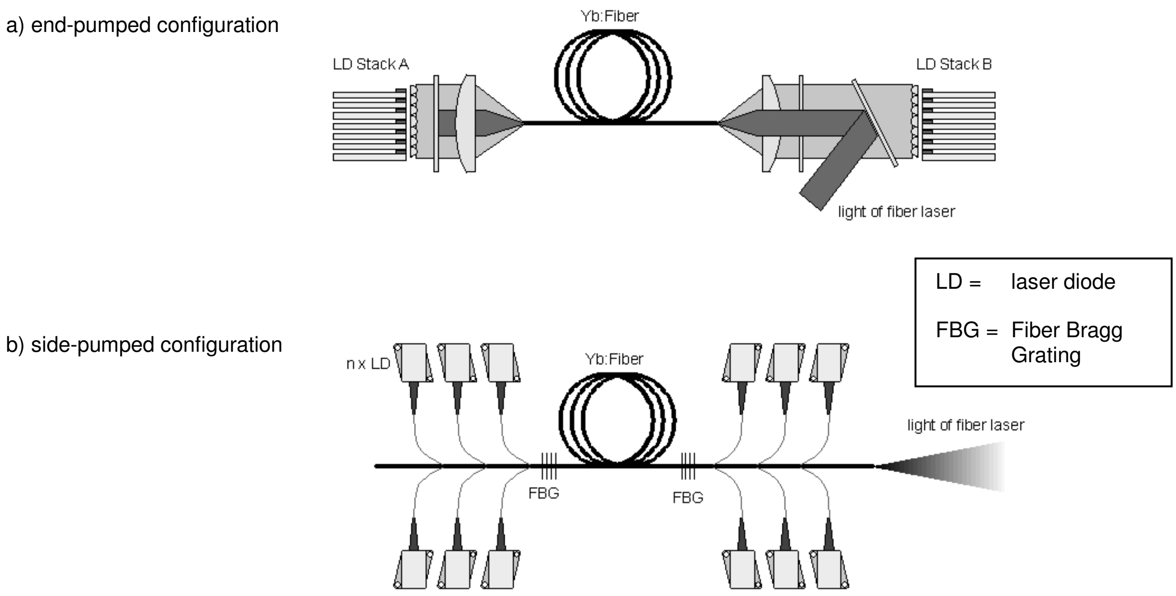

Fig. 1: Fiber laser pump configurations: a) dual end-pumped; b) distributed side-pumped.

The properties and advantages/disadvantages of these different configurations are described in the literature elsewhere. However, the required beam specifications of the pump sources can be derived directly from the design of the active signal fiber. The wavelength ot the pump beam is defined by the dopant used in the active fiber core, its beam quality (namely: beam parameter product (BPP)(a)) is given by the pump core (double-clad fiber) or the pump fibers (side-pumped fiber).

Fig. 2 shows typical fiber designs with the values for Numerical Aperture (NA) and core diameter. For the distributed side-coupling arrangement the pump source design is relatively clear: get as much power as possible from a single emitter into a 125µm / NA 0.12 fiber. For the other fiber arrangements, which require much higher power levels, various options for building a suitable pump source are feasible. Among less popular approaches like the use of SEAL (Single Emitter Array Laser) and tapered diodes, two main directions for building high brightness modules are pursued by most manufacturers:

- *Pump source based on single emitters*

  Power scaling is done either by spatial multiplexing of many single emitter devices in free space arrangements, or by means of single- or multi-stage fiber combiners .

- *Pump source based on broad-area diode laser bars*

  Diode bars in free-space arrangements are coupled directly into a high-NA pump fiber, or several high-brilliance fiber coupled devices are scaled up via fiber combiners.

(a) defined as $\boldsymbol{BPP = w_0 \cdot \theta}$ (half beam waist diameter $w_0 = d_0 / 2$ times half far field divergence angle θ)

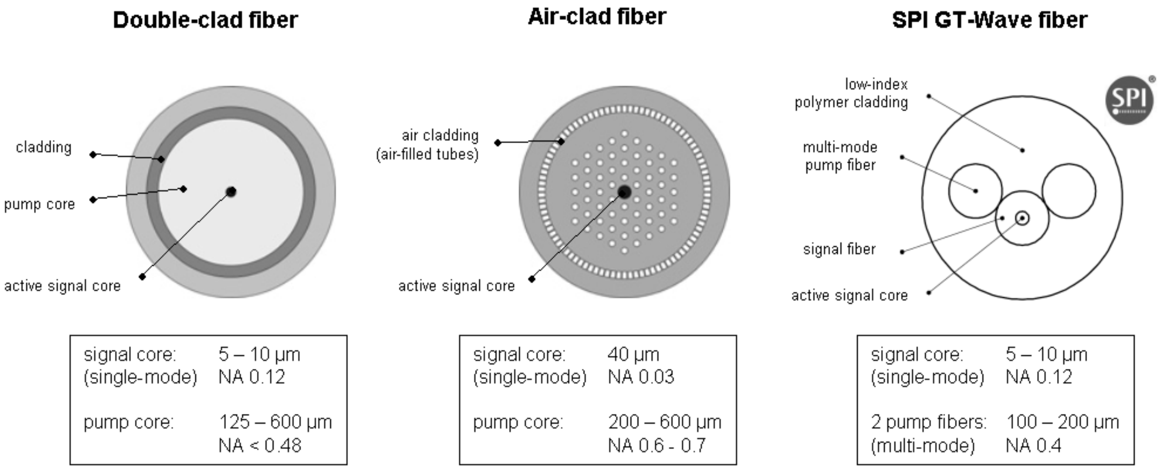

Fig. 2 Different active fiber designs.

Fig. 3 illustrates that either design approach features inherent advantages and disadvantages over the other. Consequently, over the past couple of years, among manufacturers a tendency emerged to combine advantages of the diode bar design with those of single emitters. From the bar point of view the most relevant driving forces towards this trend are given by superior cost potential and lifetime of the single emitter technology. Single emitter manufacturers, on the other hand, are looking for the brilliance of fiber coupled devices achievable with a multi-emitter array or a diode bar. Examples are given, for instance, by short-bar arrangements with 4 emitters per bar for materials processing [2] and free-space single emitter setups for fiber laser pumping.

Being a traditional diode bar packaging company, at DILAS the fusion between these two basic configurations consequently was realized by taking a conventional 10mm diode bar and including some desired properties of single emitters. The overall goal was to achieve maximum brightness at minimum cost/watt from a versatile module that can be used for both pumping and materials processing applications.

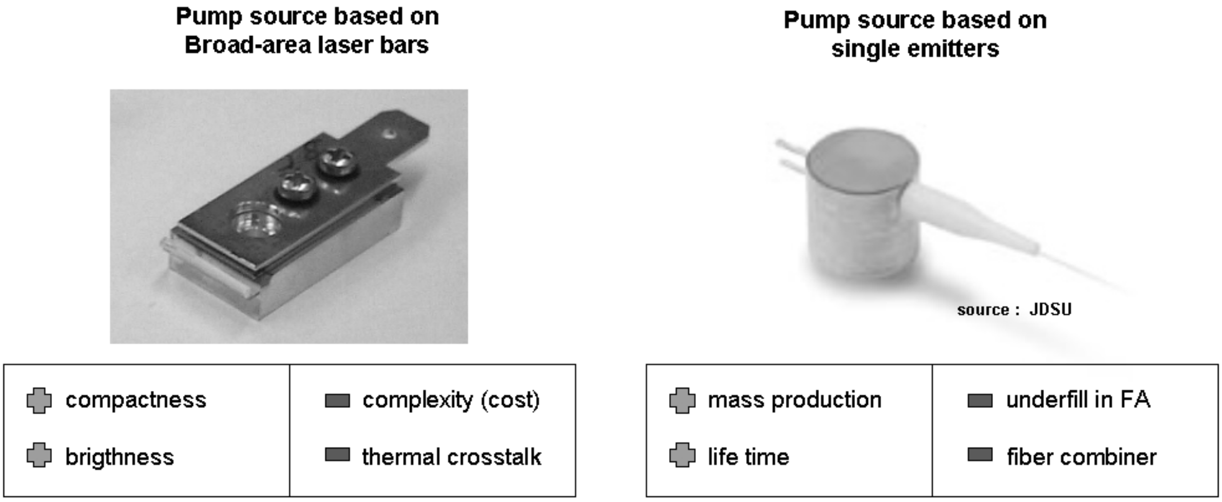

Fig. 3 Fiber laser pump sources: diode bar vs. single emitter.

2. T-BAR GENERAL DESIGN ASPECTS

T-Bar stands for tailored bar. The T-Bar is a linear array of multiple emitters, which pitch (distance from emitter to emitter) and width is chosen such that a desired beam quality in slow-axis direction can be realized without using complex beam shaping optics. In fast-axis direction, to achieve maximum brightness in a laser spot coupled into a fiber optics, the number of bars vertically arranged is adapted to the slow-axis beam quality. Generally, the tailored bar is characterized by two main criteria:

- the total of the slow-axis beam parameter products of the emitters is equal to the required beam quality of the used fiber.
- The use of µ-optics is limited to fast-axis collimator (FAC) and slow-axis collimator (SAC) to minimize aberrations and maximize fill-factor.

Designing a tailored bar follows the typical engineering steps: first the goal, i.e. the fiber parameters (diameter and NA) is defined, then the lateral structure of the emitter array is designed, and the number of bars that fit into the fiber is determined. In Table 1 this relation is depicted by means of three different fiber diameters and the corresponding Fast- and slow-axis parameters.

Table 1: Beam parameters of a diode stack derived from fiber parameters.

Fiber				**Laser diode bar**									
				slow-axis							fast-axis		
NA	core diameter	BPP_{Fiber}	BPP_{Fiber} / √2 (a)	Diver-gence (half angle)	total length of emitter line	# of emitters	possible lateral structure emitter size / pitch			BPP_{SA} total	BPP / bar	# of bars	BPP_{FA} total
	µm	mm mrad	mm mrad	°	µm		µm / µm			mm mrad	mm mrad		mm mrad
0.22	100	11	7.7	3.5	250	5	50 / 1000	50 / 500	50 / 250	7.6	1.5	5	7,5
	200	22	15.5	3.5	500	5	100 / 2000	100 / 1000	100 / 500	15.3	1.5	10	15
	400	44	31	3.5	1000	10	100 / 2000	100 / 1000	100 / 500	30.6	1.5	20	30
							5%	10%	20%				
							fill-factor on bar						

To overcome technical and economical constraints the following predominant aspects had to be considered during T-Bar development :

A) Cost

In a typical fiber coupled diode laser module main cost drivers are given by the semiconductor chips on one hand, and µ-optics on the other. In fact, the higher the brightness of the module, the more the cost pendulum shifts towards the µ-optical components. For a 200µm fiber module built with conventional 10mm diode bars the contribution of µ-optics can easily reach or exceed 50% of the total manufacturing cost. Adding expenses for alignment and mounting of sophisticated µ-optics this value may rise well above 60%. A major goal in T-Bar development was to significantly cut down this cost factor to below 20% at constant semiconductor cost. This can only be achieved by consequently eliminating complex prism and lens systems for rearranging or rotating individual emitters and limiting the use of µ-optics to collimation lenses.

B) Cooling

Another important factor directly affecting the cost/Watt value is the achievable power density on the front facet of the diode. Even with state-of-the-art mounting technologies (hard solder), standard 10mm diode bars are commercially

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(a) maximum allowed BPP to avoid overfilling of the fiber when a square laser beam is incident.

available with max. 25W/mm emitter line. Single emitters, on the other hand, currently are available at power levels between 50 and 100 W/mm, with predicted values of up to 200W/mm. This discrepancy is caused mainly by thermal reasons: even when using µ-channel heat sinks, cooling of a densely packed diode bar is significantly less efficient than cooling a single emitter, which is, for instance, mounted on a C-mount heat sink.

Apart from the cost factor, efficient cooling greatly affects performance and life-time of the diodes. Simulations show that in a typical diode bar thermal crosstalk between adjacent emitters accounts for a very significant part of the heat build-up within the semiconductor. This is especially true for high fill-factor bars (e.g. 50%) and non-optimum thermal resistance, as evident in hard-soldered laser diode with copper-tungsten sub-mount. The only cure for thermal crosstalk is distance between emitters. On the chip level, this measure, however, contradicts the low-cost criterion: high pitch means low fill-factor, which in turn means that much of the expansive semiconductor material is inactive. In addition, subsequent FAC and SAC lenses also become less cost efficient when the fill-factor of the diodes is reduced. An iterative approach based on thermal simulations has been carried out when designing the T-Bar to find the best compromise between cost and performance.

C) Beam quality

The required beam parameters of a linear emitter array can easily be calculated from the diameter and numerical aperture (NA) of a desired fiber. Usually, for a given epitaxial structure and cavity length the slow-axis divergence of a laser diode is a function of current density, and thus of optical power. Once the operational point of a diode is determined, the resulting beam divergence can be used to calculate the total length of the emitter line to realize a certain beam parameter product. The length of the emitter line together with the cooling constraints define the lateral structure of the tailored bar. For instance, one 500µm emitter has the same beam quality than five 100µm emitters evenly distributed on a 10mm diode bar. However, cooling of the low fill-factor bar will be much more efficient.

In addition to the cooling aspect, a low fill-factor improves the performance of the slow-axis collimation, improving overall slow-axis beam quality. On the other hand, assuming similar mounting technology, a long low fill-factor bar is much more susceptible to fast-axis beam aberrations caused by smile than a short high fill-factor bar. Again, the DILAS T-Bar was designed to best meet these contradictory effects.

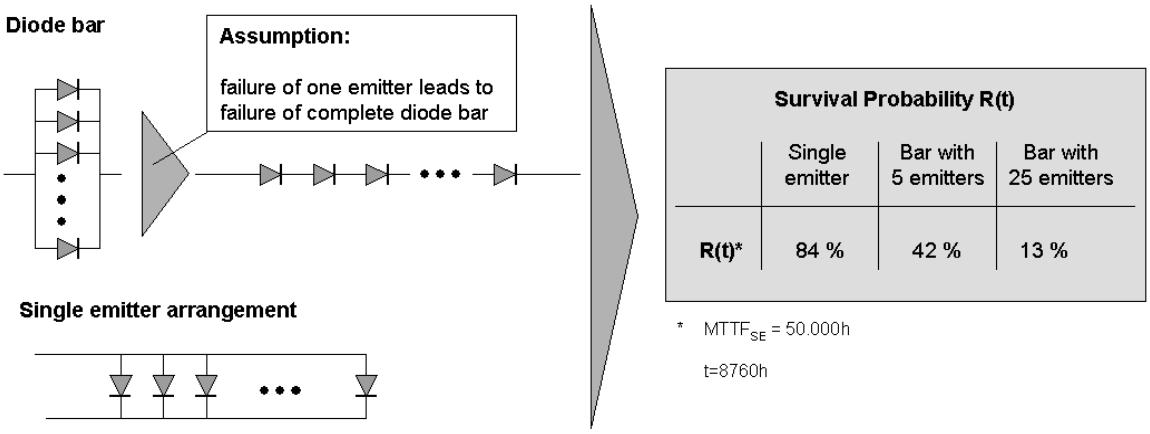
D) Life time

The typical lifetime of 10mm bars is 10-20,000 hours, depending on operation mode and environmental conditions. In sharp contrast to these figures are the values for single emitter devices, which usually lay well above 50,000 hours. Apart from technical aspects (cooling, internal stress etc.) single emitter arrangements have an inherent advantage over diode bars: electrical and environmental isolation. On a bar a certain number of emitters are arranged in a very tight package being all connected in parallel. This lack of spatial and electrical isolation may result in the fatal situation that the failure of one emitter leads to the failure of the complete diode bar due to a short-cut or by contaminating the facet of the other emitters. This dependence leads to a block diagramm, where the individual emitters of the diode bar are arranged in series (Fig. 4). Single emitter devices can be connected such that the failure of one emitter does not affect the others. Therefore, on a MTTF based calculation the survival probability R(t) within a given operational time t of a completely in parallel connected array of single emitters is much higher than for a diode bar:

$$R(t) = 1 - F(t) = e^{n(-\lambda t)} \qquad \text{with} \qquad \lambda = \frac{1}{MTTF}, \qquad (1)$$

where MTTF is the mean time to failure value, F(t) is the failure probability, and n the number of diodes in series.

In reality, the difference between single emitter and diode bar is not as dramatic as depicted in the table of Fig. 4, since by far no every emitter failure results in the loss of a complete bar. However, from a statistical point of view, reducing the number of emitters on a diode bar is an efficient means to increase lifetime. To account for that fact, the DILAS T-Bar comprises much less emitters than standard diode bars.



Survival Probability R(t)	Single emitter	Bar with 5 emitters	Bar with 25 emitters
R(t)*	84 %	42 %	13 %

* $MTTF_{SE}$ = 50.000h

t=8760h

Fig. 4 Block diagramm and survival probability of diode bar and single emitter arrangement.

3. DESIGN AND PERFORMANCE OF 500W / 200 µM PROTOTYPE

The predominant aspect for the optical layout of the T-Bar module was simplicity and efficiency, both greatly affecting costs per Watt. Fig. 5 shows the optical setup of the 500W prototype. The diodes are arranged in two polarisation coupled blocks, each comprising two interleaving rows of diodes. Stacking in fast-axis direction is realized by means of a stepped base plate. To adapt the beam path of front and rear diodes a novel optical element is introduced, which not only deflects and interleaves the beams of the individual diodes but also compensates for beam path differences. In SA direction, no further beam shaping is required. In FA direction, to realize a symmetrical beam on the focussing lens, the beam is compressed with a cylindrical telescope. Focussing into a 200µm mode stripped fiber is done with a set of spherical lenses.

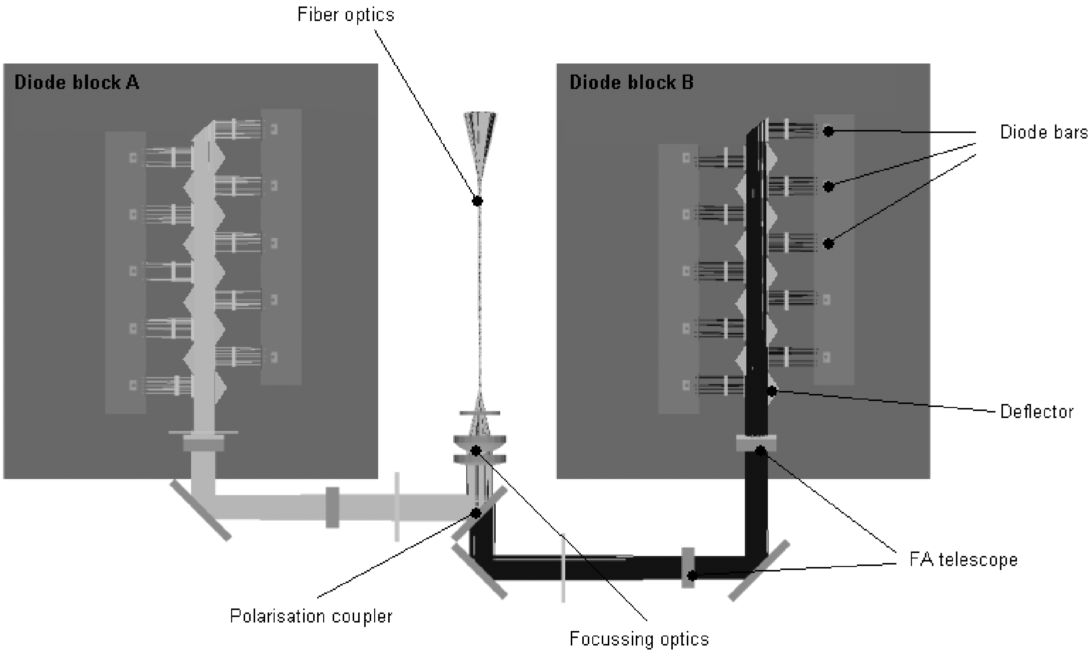


Fig. 5 Optical setup of fiber coupled module.

The brightness level aimed at within this project requires a rigid and thermally stable mechanical setup to ensure reliable operation. A stiff single-frame case carrying all optics mounts and the diode base plates is used to meet the criteria for stiffness, compactness and simplicity. The center position of the fiber allows the use of a conduction cooled fiber connector. Cooling is realized by means of a common inlet for the two diode blocks and the fiber base plate. The passive cooling strategy allows the use of industrial water, which is strictly banned from the interior space of the module housing. Fig. 6 shows a 3D drawing of the module with preliminary high power fiber adapter. The overall size is 250 x 150 x 40 mm^3.

Fig. 6 3D drawing of prototype T-Bar module with high power fiber adapter.

A major part of further development is the design of a conduction cooled low-cost fiber capable of handling up to 1 kW CW power. Since at the time of this publication no such fiber was available yet a standard water cooled high power fiber was used. In Fig. 7 the optical performance of the first prototype module is depicted. The PI (Fig. 7a) curve shows that the aimed output power of 500W ex 200µm fiber was achieved at a current level of ~39A. The main issue of ongoing development will address a drop in efficiency with increasing current, evident by the bend in the PI curve.

The homogeneous spectrum of the module (Fig. 7b) proves that heat dissipation from the individual heat sinks over the base plate to the cooling water is sufficiently efficient.

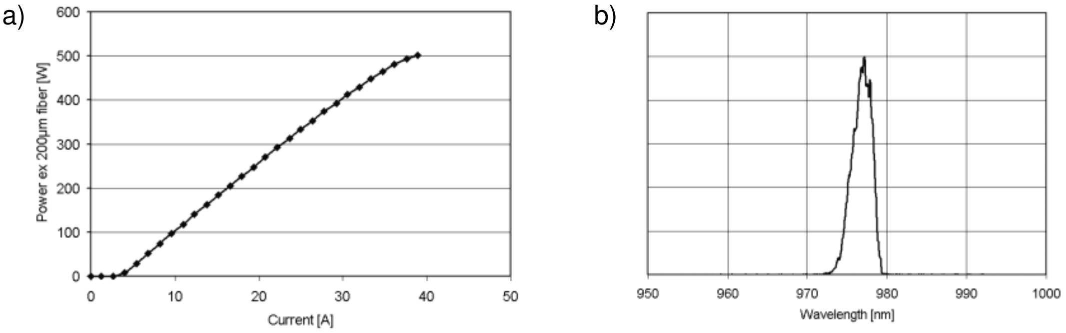


Fig. 7 PI curve and wavelength of the prototype module ex 200µm high power fiber @ 20° water temperature.

4. CONCLUSION AND PROSPECTS

Using a new approach of diode bar design, at DILAS a high-brightness fiber coupled laser module has been developed. With cost reduction as predominant goal, the main criteria for the optical and mechanical layout were simplicity and efficiency. With a first prototype an output power of 500W from a 200µm mode stripped fiber at 976nm could be demonstrated. Combining the technical advantages of diode bars and single emitter based systems the T-Bar module is capable of becoming a high-potential fiber laser pump source.

Further development goals direct towards improvements of the laser diode as well as the overall module design. Especially progress on the chip level has the potential to significantly cut cost per Watt and increase lifetime. For the prototype module, normalized to a 100µm emitter stripe, power was limited to 6W per emitter. In the near future output power levels of well above 10W are expected, having the effect of both increasing brightness of the module and reducing cost/Watt. A feasible value here should be <20$/Watt ex fiber.

Improvements of the module design address, among others, heat dissipation and handling. Reduction of the thermal resistance between the diode bar and the water circuit has a tremendous impact on the performance and lifetime of the semiconductor. Innovative mounting technologies in order to reduce the number of thermal interfaces, and the use of alternative materials, like CVD diamond or composites, are being investigated in this project. The desire for easy handling ultimately leads to the "disposable module" philosophy. Here, the design goal is a completely maintenance free module with superior lifetime, which, despite its complexity and total cost, can be disposed after use similar to much smaller single emitter devices.

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