

# High-power diode laser modules from 410 nm – 2200 nm

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## 1 ABSTRACT

In this work we report on high-power diode laser modules covering a wide spectral range from 410 nm to 2200 nm. Driven by improvements in the technology of diode laser bars with non-standard wavelengths, such systems are finding a growing number of applications. Fields of application that benefit from these developments are direct medical applications, printing industry, defense technology, polymer welding and pumping of solid-state lasers.

Diode laser bars with standard wavelengths from 800 – 1000 nm are based on InGaAlAs, InGaAlP, GaAsP or InGaAs semiconductor material with an optical power of more than 100 W per bar. For shorter wavelengths from 630 – 690 nm InGaAlP semiconductor material is used with an optical power of about 5 W per bar. Extending the wavelength range beyond 1100 nm is realized by using InGaAs on InP substrates or with InAs quantum dots embedded in GaAs for wavelengths up to 1320 nm and (AlGaIn)(AsSb) for wavelengths up to 2200 nm. In these wavelength ranges the output power per bar is about 6 – 20 W.

In this paper we present a detailed characterization of these diode laser bars, including measurements of power, spectral data and life time data. In addition, we will show different fiber coupled modules, ranging from 638 nm with 13 W output power (400  $\mu$ m fiber, NA 0.22) up to 1940 nm with more than 50 W output power (600  $\mu$ m fiber NA 0.22).

**Keywords** : High-power diode laser, broad area diode laser, fiber coupling, eye-safe, InGaAlP, GaSb diode laser

## 2 INTRODUCTION

High-power diode laser systems are well established laser sources for a variety of applications including materials processing and solid state laser pumping. The main advantages of such systems are high wall-plug efficiency, high optical power, reliability, long lifetime, relatively low investment costs and a small footprint.

For a long period high-power diode laser bars with multiwatt output power were only available in a wavelength range between 800 and 980 nm. In the last few years significant improvements in the semiconductor technology like progress in the epitaxial growing process and the development of new material combinations have taken place. As a consequence the wavelength range for high-power diode laser bars has been extended to shorter wavelengths down to 400 nm and to longer wavelengths up to 2200 nm.

The extension of the wavelength range opened up new markets for high-power diode laser bars. For wavelengths below 800 nm one important application is photodynamic therapy in the red spectral range around 640 nm. Further potential applications in the visible spectral range are in the area of optical displays. For wavelengths above 1000 nm important applications are plastic welding and medical treatment. In Sect. 5 these applications are described in more detail.

The majority of applications requires fiber coupled systems, where the diode laser beam of the bar is coupled into an optical fiber to transport the light to the application. In addition fiber coupling also homogenizes the beam by multiple reflections inside the fiber which is important for many applications. However, one drawback of standard broad area diode laser bars is their relatively poor beam quality and brightness as defined in Equ. (1). The brightness of a diode laser beam is defined by the laser power  $P$  and the beam parameter product (BPP)<sup>a</sup> in slow- and fast-axis-direction<sup>1</sup>.

$$B = \frac{P}{\pi^2 \cdot BPP_{total}^2} \quad ; \quad BPP_{total}^2 = BPP_{slow}^2 + BPP_{fast}^2 \quad ; \quad BPP^{diffraction\ limited} = \frac{\lambda}{\pi} \quad (1)$$

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<sup>a</sup> defined as  $BPP = w_0 \cdot \theta$  (half beam waist diameter  $w_0 = d_0/2$  times half far field divergence angle  $\theta$ )

The output beam of a common broad area diode laser bar is characterized by a highly asymmetric profile with regard to beam dimension and divergence angle. Typical values for the source width are 10 mm for the lateral direction in the plane of the pn-transition (slow-axis) and 1  $\mu\text{m}$  for the vertical direction (fast-axis), respectively. The beam divergence angles are typically  $35^\circ$  in fast-direction and  $5^\circ$  in slow-direction, respectively<sup>a</sup>. Consequently, the resulting beam parameter products are highly asymmetric. Whereas the beam quality in the fast-direction is about 1 mm-mrad and thus nearly diffraction limited, the beam quality in the slow-direction is in the region of 400 - 500 mm-mrad, which is far beyond the diffraction limit. Efficient fiber coupling of such a diode laser bar is only possible if the different BPPs are adapted by shifting beam quality from one direction to the other. This symmetrization of the BPPs is equivalent to a minimization of the overall beam parameter product  $\text{BPP}_{\text{total}}$ .

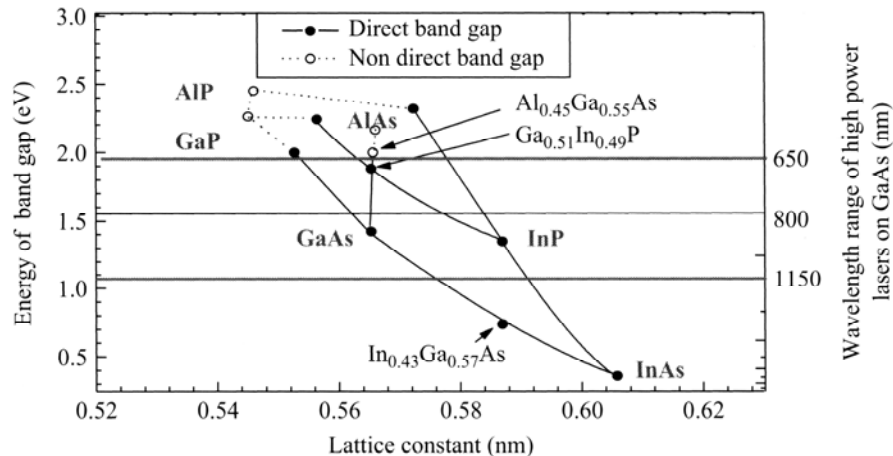
The minimum value for the beam parameter product is the so-called diffraction limit and is depending on the wavelength  $\lambda$ . For a given wavelength  $\lambda$  the diffraction limited BPP is calculated by  $\lambda/\pi$  (cf. Equ. (1)), which means that the beam quality of the diode laser bar scales with the wavelength. However, the beam quality which is required for efficient coupling into an optical fiber does not primarily depend on the wavelength and is only defined by the fiber core diameter and the numerical aperture. In consequence this means that fiber coupling becomes more difficult when moving to longer wavelengths.

### 3 DIODE LASER BARS FOR NON-STANDARD WAVELENGTHS

#### 3.1 Basic considerations for the design of semiconductor diode lasers in different wavelengths regions

Semiconductor diode lasers are produced by using epitaxial growth techniques. In these processes, very thin lattice-matched layers are deposited onto GaAs or InP substrate wafers. The properties of the diode lasers are defined by the material composition and the doping profile of the multilayer structure. In modern semiconductors the active region is only about 10 nm surrounded by material with a larger band gap. This quantum-well structure has several advantages like low threshold, high material gain and lower spectral shift of the gain curve.

The most important advantage is that quantum-well structures allow to introduce compressive or tensile mechanical strain. Therefore the wavelength range can be extended by using material compositions with lattice constants that does not fully match the lattice constant of GaAs. By replacing gallium partly with indium the wavelength can be shifted up to 1100 nm. By replacing arsenic with phosphorus the wavelength range can be shifted down to 730 nm. Fig. 1 shows III/V semiconductor compounds which can be epitaxially grown on GaAs and InP substrates.



**Fig. 1:** Band gap energy of III/V compound semiconductors as a function of lattice constant. The binary compounds are represented by dots, ternary alloys are drawn as lines. The right axis shows the corresponding wavelength<sup>1</sup>.

<sup>a</sup> the divergence angles are defined as half far field divergence angle ( $1/e^2$  - value)

The wavelength of the semiconductor lasers is determined by the size of the band gap, which is defined by the composition of the crystal. This is also shown in Fig. 1 as a function of lattice constant. Table 1 shows typical compositions of quantum wells for different wavelengths<sup>1,2</sup>.

High-power semiconductor lasers emitting in the 0.8-1.0  $\mu\text{m}$  wavelength region are typically realized on GaAs and alloys lattice-matched to GaAs. When moving to longer wavelengths, the use of GaAs becomes problematic because of the increasing mismatch between the lattice constant of the substrate and the epitaxial layers of the quantum well. This mismatch induces compressive strain, which in turn decreases the gain of the semiconductor laser diode. Therefore, for wavelengths between 1380 nm and 1550 nm, the wafer substrate material is changed to InP. However, such diode laser bars are only capable of emitting lower power levels when compared to standard diode laser bars in the spectral region from 780 – 1000 nm (cf. Table 1).

When emission wavelengths in the 1850 – 2200 nm range are required, the material system again switches from InP to GaSb-based structures, which have been shown to operate at power levels of 10 – 20 W per bar. The progress in fabrication technology and design of layer structure not only led to the development of diode laser bars with wavelengths outside the standard wavelength range, but also improved the performance of standard diode laser bars. Among these improvements are higher output power (up to 60 – 80 W conductively cooled) and longer lifetimes (> 10 000 to 20 000 h). In addition, significant improvements have been achieved with regard to the slow-axis divergence which becomes especially important for fiber-coupled diode laser modules. Improvements of the slow-axis divergence can only be made at the epitaxial level by modifying the waveguide and cladding layers, or by lithographic optimizations of the lateral structure of the laser diode array.

In the following sections the characterization of different diode laser bars from 415 nm up to 2200 nm will be presented.

**Table 1:** Emission wavelengths of various types of diode laser bars

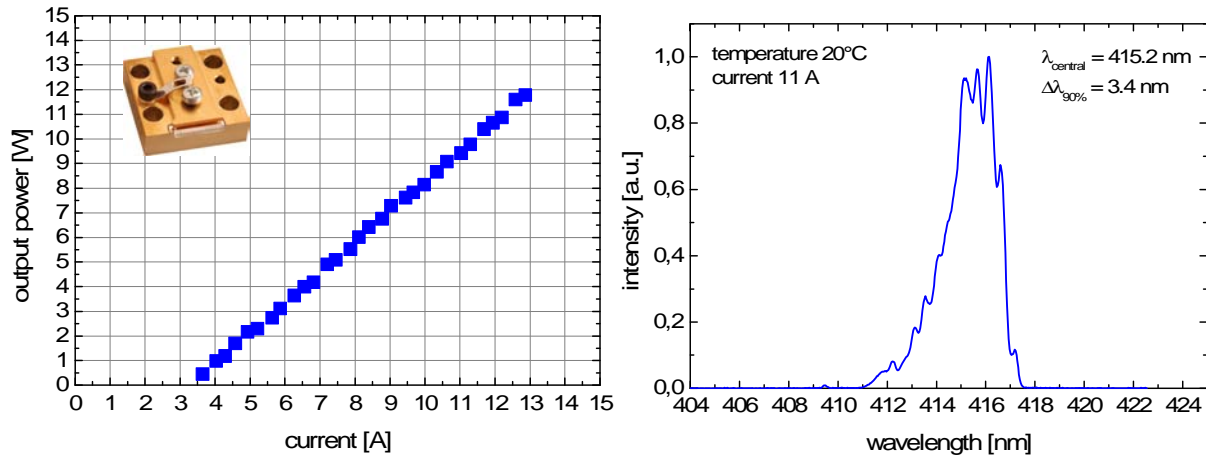
quantum well material	wafer substrate	wavelength [nm]	power per bar [W]
InGaN	GaN	400 - 420	> 4
InGaAlP	GaAs	630 - 690	> 5
GaAsP	GaAs	780 - 810	50 to > 100
InGaAlAs	GaAs	790 - 830	50 to > 100
AlGaAs	GaAs	720 - 850	50 to > 100
$\text{In}_{0.08}\text{Ga}_{0.92}\text{As}$	GaAs	880	50 to > 100
$\text{In}_{0.10}\text{Ga}_{0.90}\text{As}$	GaAs	940	50 to > 100
$\text{In}_{0.12}\text{Ga}_{0.88}\text{As}$	GaAs	980	50 to > 100
$\text{In}_{0.15}\text{Ga}_{0.85}\text{As}$	GaAs	1060	> 50
InAs quantum dot	GaAs	1064 - 1320	30 - 40
InGaAsP	InP	1380 - 1550	> 20
AlGaIn-AsSb	GaSb	1850 - 2200	> 10

### 3.2 Diode laser bars in the blue-violet spectral range

The development of diode laser sources in the blue-violet spectral range around 410 nm is mainly driven by the needs for optical disc storage, which ended in the Blu-Ray disc format. Blu-Ray discs use a blue diode laser, operating at 405 nm to read and write data which allows to store almost six times more data compared to a standard DVD. Conventional DVDs or CDs use red and near-infrared diode lasers at 650 nm and 780 nm, respectively. Although for data storage applications single emitter diodes are used, the progress in semiconductor technology can be adapted to fabricate diode laser bars in that spectral range.

Fig. 2 shows an example of a diode laser bar operating at a wavelength of 415 nm. The maximum output power of the diode laser bar was 12 W at an operating current of 13 A. The right diagram of Fig. 2 shows the corresponding spectrum at a current of 11 A. The spectral distribution was centered at 415.2 nm with a spectral width of 3.4 nm (90 % power content value). The filling factor of the bar was 20 %, which makes it suitable for high brightness applications. With

appropriate beam collimation in fast- and slow-axis direction the beam quality allows efficient fiber coupling into a 800  $\mu\text{m}$  NA 0.22 fiber. With additional optics for beam symmetrization the fiber core diameter could be reduced further.



**Fig. 2:** Power vs. current curve for an InGaN blue-violet diode laser bar at 20°C. The right diagram shows the corresponding spectrum at a current of 11 A. The diode laser bar was mounted on a passively cooled heatsink.

### 3.3 Diode laser bars with wavelengths from 630 – 675 nm

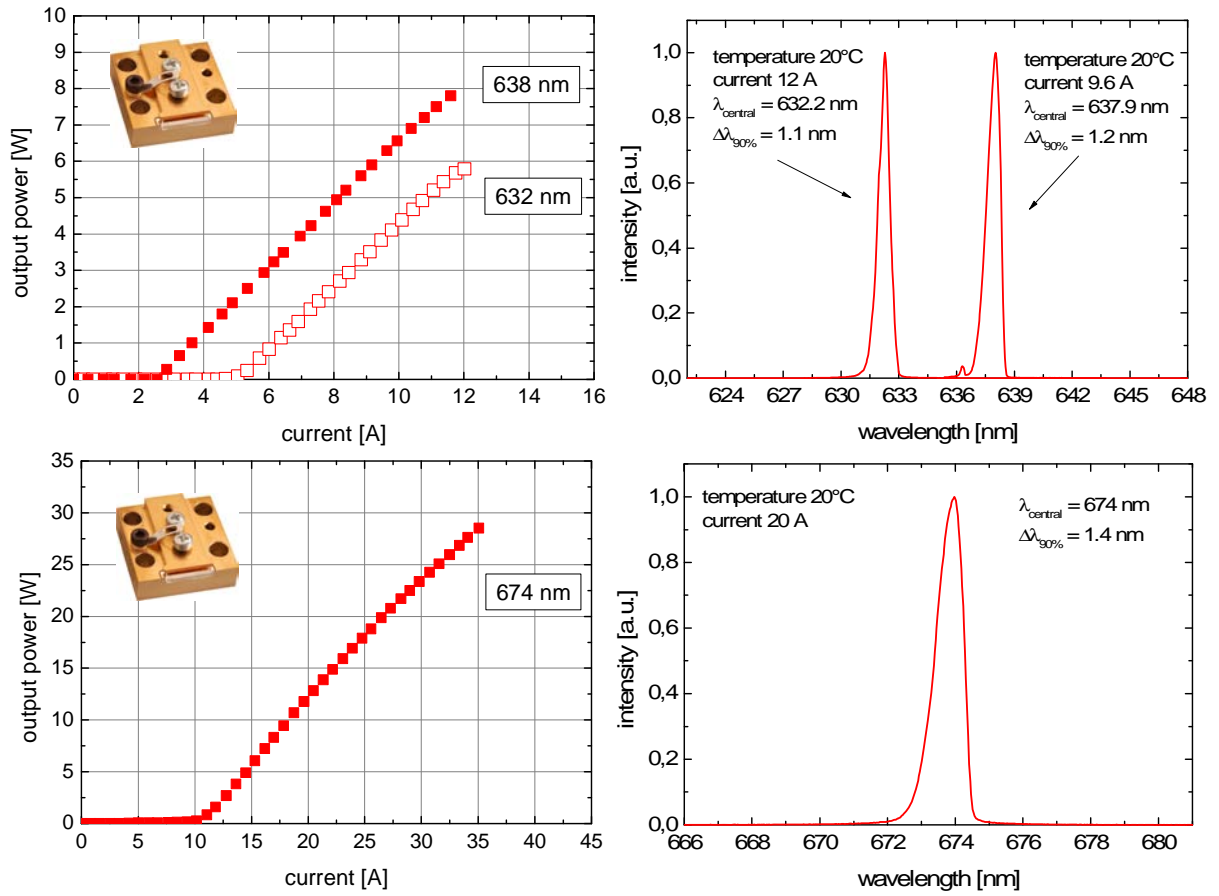
The red wavelength range can already be covered with standard GaAs wafer substrate and InGaAlP as material for the quantum well. Table 2 shows a comparison of typical data for different diode laser bars in the red spectral region from 632 to 675 nm. It is evident that power conversion efficiency and maximum output power increase with wavelength. Whereas the typical output power at 632 nm is only 4 W, it increases up to 20 W at 675 nm. The corresponding efficiency rises from 15 % up to 33 %.

Fig. 3 shows typical power vs. current dependencies and the corresponding spectra for three different wavelengths of 632 nm, 638 nm and 674 nm, respectively. All diode laser bars have a low fill factor of 10 - 20 %, which is important for beam shaping with regard to fiber coupled modules. The maximum output power was 5.8 W at 632 nm, 7.8 W at 638 nm and 28 W at 675 nm, respectively.

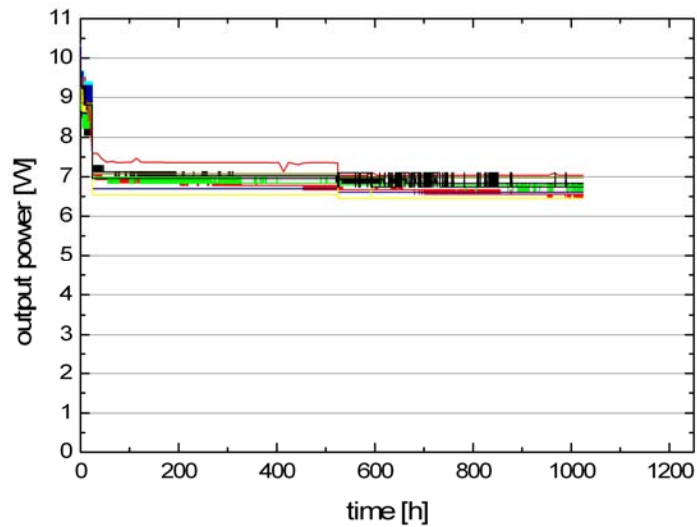
For industrial applications life time issues are at least as important as wavelength, beam quality and brightness. Fig. 4 shows a 1000 h lifetime test for 638 nm diode laser bars. The bars were mounted on conduction cooled heatsinks. The lifetime test was performed for nine different samples at an operating current of 12 A and a temperature of 20°C. No failure was observed after 1000 h. However, during the first 10 – 20 h a significant power drop of about 1 – 2 W is observed for all bars, which is a typical behavior of diode laser bars in that spectral region. After this initial power drop the output power remains stable over the whole period of 1000 h.

**Table 2:** Typical data of conduction cooled, visible single diode laser bars in the red spectral range. Data are shown for 20°C cold plate temperature.

center wavelength	632 nm	635 nm	638 nm	650 nm	675 nm
tolerance [nm]	$\pm 1.5$	$\pm 3$	$\pm 3$	$\pm 3$	$\pm 3$
typical output power [W]	4	4	8	10	20
emitter size [ $\mu\text{m}$ ]	50	50	40	100	100
number of emitters	19	19	20	20	19
fill factor [%]	10	10	20	20	20
power conversion efficiency [%]	> 15	> 25	> 30	> 25	> 33
operating current [A]	< 10	< 9.5	< 14	< 20	< 30
wavelength temperature coefficient [nm/°C]	$\sim 0.16$	$\sim 0.16$	$\sim 0.16$	$\sim 0.16$	$\sim 0.16$



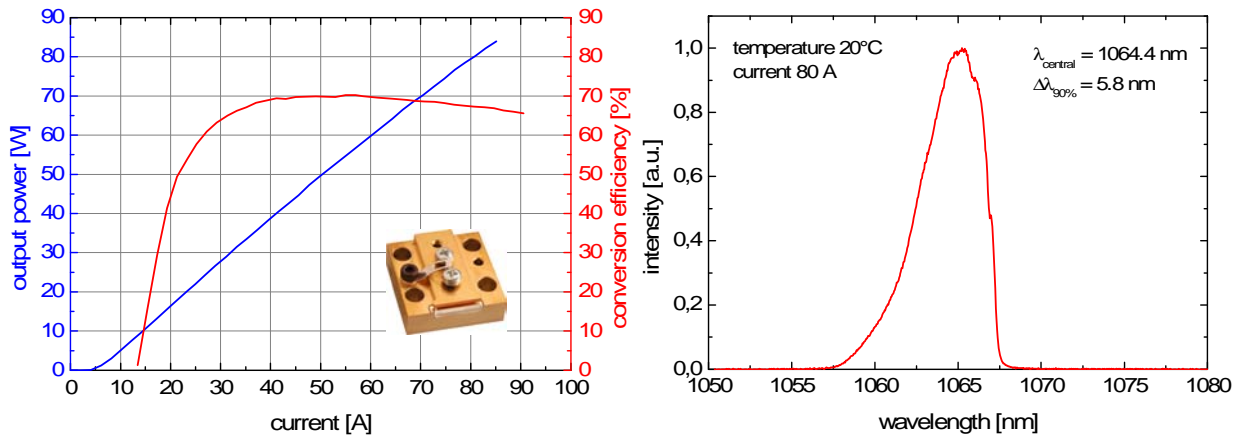
**Fig. 3:** Power vs. current curve for three different types of diode laser bars in the red spectral range from 632 nm to 674 nm. All data are shown for a temperature of 20°C. Detailed data are summarized in Table 2.



**Fig. 4:** 1000 h lifetime test on 638 nm diode laser bars mounted on passively cooled heatsinks with a current of 12 A and a temperature of 20°C. The test was performed with nine diode laser bars.

### 3.4 Diode laser bars with wavelengths above 1000 nm

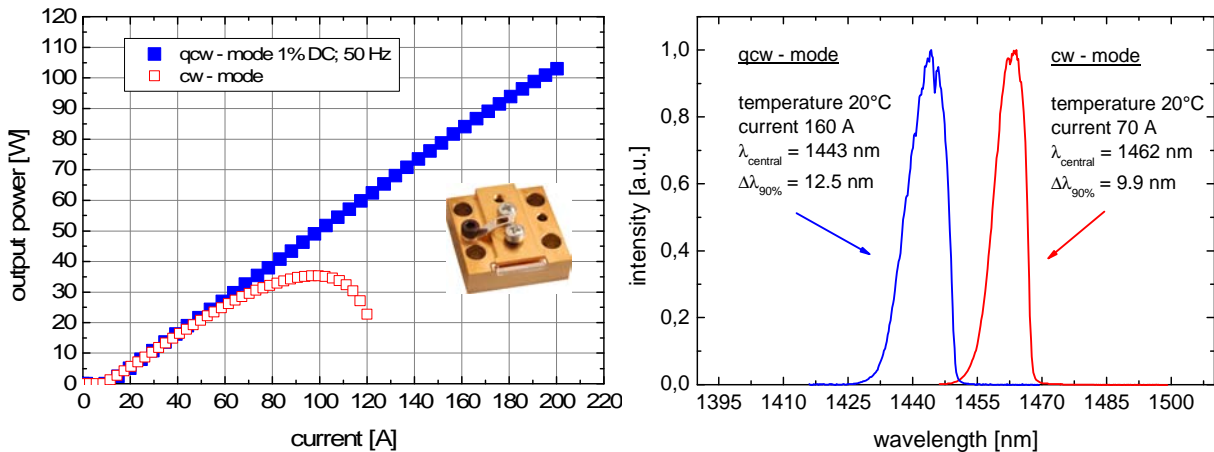
In Sect. 2.1 it was described that the wavelength of InGaAs/GaAs semiconductor lasers can be shifted towards longer wavelengths by replacing gallium partly with indium. For the important wavelength of 1064 nm (typical emission wavelength of Nd:YAG solid state lasers) the use of the standard material composition InGaAs/GaAs is still possible and allows for relatively high output power and efficiency comparable to the data in the spectral region from 880 – 1000 nm. Fig. 5 shows the characteristic data of such a diode laser bar mounted on a passively cooled heatsink. The maximum output power was 84 W at a current of 85 A. The maximum efficiency exceeded 70 % at a current of 50 A.



**Fig. 5:** Power vs. current curve for an InGaAs/GaAs diode laser bar at 1064 nm and a temperature of 20°C. The right diagram shows the corresponding spectrum. The diode laser bar was mounted on a passively cooled heatsink.

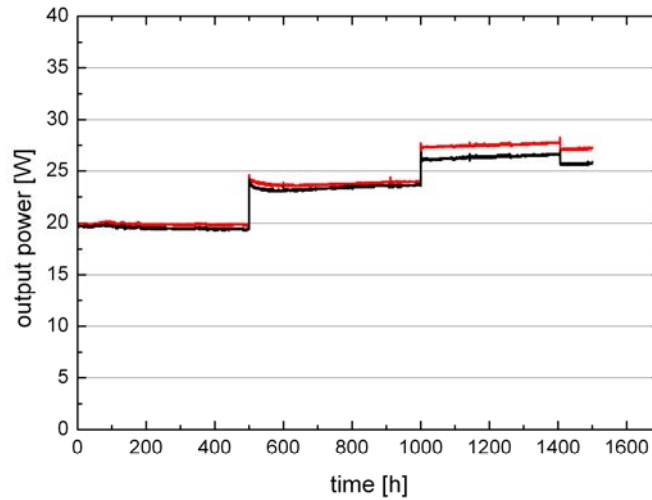
The emission range of GaAs-based semiconductor lasers can be extended beyond 1100 nm by using semiconductor quantum dots instead of quantum wells. With this technique wavelengths up to 1320 nm can be realized with InAs/GaAs semiconductor compound material system. The lasing wavelength is controlled between 1064 nm and 1320 nm by quantum dot size, distribution, and indium concentration.

For wavelengths above 1300 nm the semiconductor material has to be changed to InGaAsP quantum well structures on InP wafer substrate. Fig. 6 shows an example for a 1470 nm diode laser bar.



**Fig. 6:** Power vs. current curve for an InGaAsP/InP diode laser bar at 1470 nm for continuous-wave (cw) and quasi-continuous-wave (qcw)-operation at a temperature of 20°C. For qcw-operation the repetition rate was 50 Hz with 1 % duty-cycle (DC). The right diagram shows the corresponding spectra. The diode laser bar was mounted on a passively cooled heatsink.

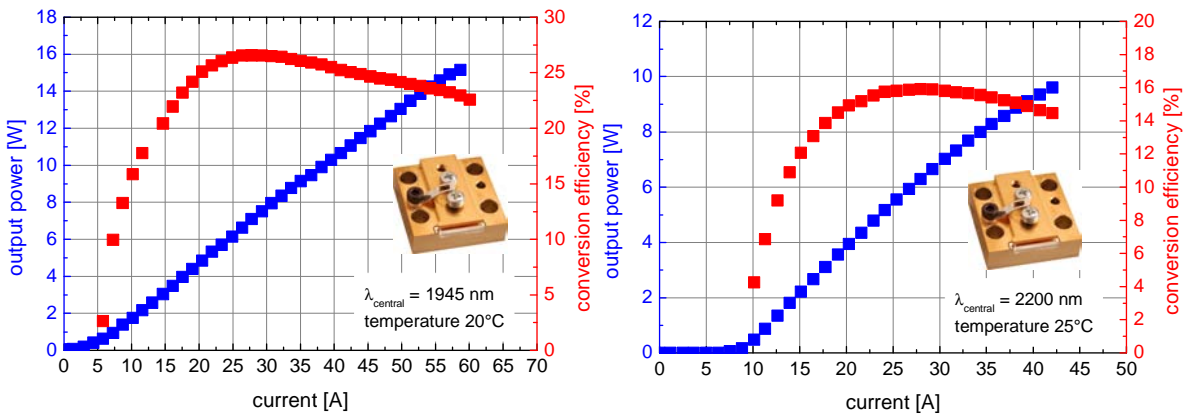
The left diagram of Fig. 6 shows the power vs. current characteristics for two different modes of operation. In continuous-wave (cw)-mode the maximum output power was about 35 W and limited by thermal-roll-over effect. However, no COD has been observed up to a current of 120 A. In quasi-continuous-wave (qcw)-mode operation the output power exceeded 100 W at a current of 200 A. The corresponding spectra are shown in the right diagram of Fig. 6. A lifetime test showed stable operation of more than 1500 h in cw-mode (cf. Fig. 7). The output power was raised stepwise after each 500 h period by increasing the current by 10 A. The power drop at the end of the test was caused by a calibration effect.



**Fig. 7:** 1500 h lifetime test on 1470 nm diode laser bars mounted on passively cooled heatsinks at a temperature of 20°C. After each 500 h period the current was increased by 10 A up to 70 A in the final stage. The test was performed with two diode laser bars.

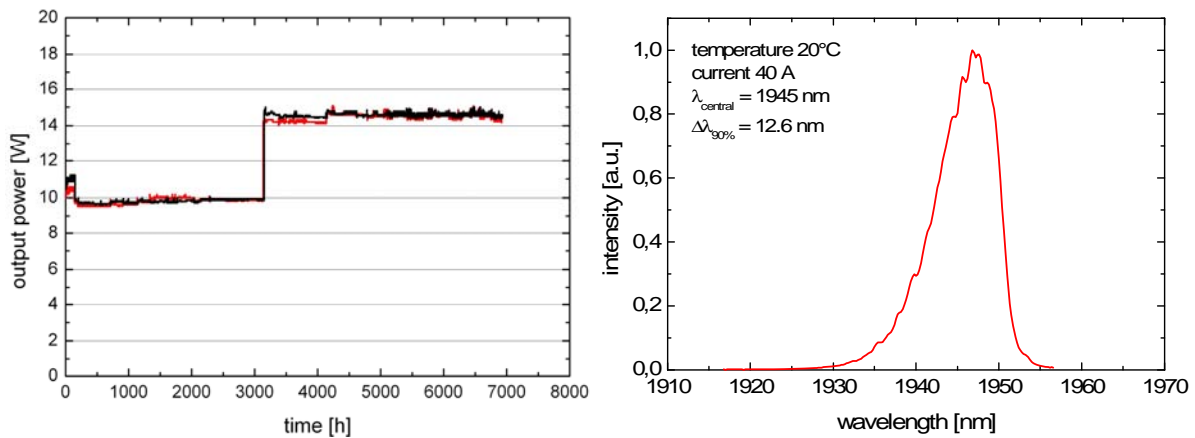
Similar characteristics are achieved with semiconductor material lasing at 1540 nm. Output powers up to 27 W in cw-mode and up to 115 W in qcw-mode have been achieved. In addition lifetime test up to 1500 h in cw-mode with 23 W output power have been performed.

For wavelengths > 1900 nm the semiconductor compound material system has to be changed again. In this spectral range GaSb is used as wafer substrate material and (AlGaIn)(AsSb) is the compound material for the quantum well<sup>3</sup>. Fig. 8 shows two examples of diode laser bars with this material combination at two different wavelengths of 1940 nm and 2200 nm, respectively. The 1940 nm-bar achieved a maximum output power of 15 W at a current of 60 A with a wall-plug-efficiency of 23 %. The maximum efficiency was 27 % at a current of 30 A. The maximum output power for the 2200 nm-bar was 9.6 W at a current of 42 A with a corresponding efficiency of 14.5 %.



**Fig. 8:** Power vs. current curve for (AlGaIn)(AsSb) diode laser bars at 1940 nm (left diagram) and 2200 nm (right diagram). The diode laser bar were mounted on passively cooled heatsinks.

Fig. 9 shows a lifetime test for 1940 nm diode laser bars and a typical spectrum of such a bar. The spectral distribution was centered at 1945 nm and the spectral width was 12.6 nm. The lifetime test was performed for two different diode laser bars. The lifetime test started with an operating current of 40 A corresponding to an optical output power of about 10 W. After 3000 h the output power was raised to 15 W by increasing the current up to 55 A. The test was performed for two different diode laser bars and no failure has been observed up to a running period of 7000 h.



**Fig. 9:** 7000 h lifetime test for (AlGaIn)(AsSb) diode laser bars at a wavelength of 1940 nm (left diagram) and typical spectrum of a 1940 nm bar (right diagram). After 3000 h the current was increased from 40 A up to 55 A.

## 4 DIODE LASER MODULES WITH NON STANDARD WAVELENGTHS

### 4.1 Design considerations for diode laser modules with non standard wavelengths

In this section we present a couple of different modules based on diode laser bars with non standard wavelengths. The availability of such bars with high-power and the specific requirements of new applications enforced the development of new diode laser modules outside the standard wavelength range.

Based on the diode laser bars presented in the previous section, diode laser modules can be customized to the specific demands of various applications. Among these demands could be a specific output power, beam divergence in slow- and fast-axis direction, wavelength stability, an appropriate spot size in the focal plane or the demand for a fiber coupled solution. To fulfill these requirements different assemblies are possible, like an uncollimated single bar as a very simple setup, one or two dimensional arrays of diode laser bars with or without microoptical elements for beam collimation and complete fiber coupled solutions with appropriate beam symmetrization.

In the following we will concentrate on fiber coupled modules, because the majority of applications asks for a fiber coupled solution. It is important to notice that building such modules is not completed by simply replacing the diode laser bars in standard diode laser modules. Some important design issues have to be considered while building diode laser modules with a non-standard wavelength :

- the beam parameter product (BPP) scales with the wavelength, which means that the beam quality gets worse with increasing wavelength (cf. Equ. 1). However, for fiber coupled systems a specific BPP product is needed for efficient fiber coupling, so that the number of emitters that can be coupled into an optical fiber decreases quadratically with the wavelength. For a module at 1800 nm the number of emitters that can be coupled into a fiber decreases by a factor of 4 compared to a module at 900 nm. In combination with the lower output power of the bar itself, the total power of fiber coupled systems above 1000 nm will decrease significantly, if compared to standard modules in the range from 800 - 1000 nm

- the slow-axis divergence typically increases with wavelength, which means that the focal length of the slow-axis collimation lenses (SACs) has to be adapted to avoid losses at the SAC
- for some bars with non-standard wavelengths the divergence in the fast-axis direction is relatively high with a full angle of up to  $90^\circ$ , which requires fast-axis collimating lenses (FAC) with high numerical aperture and good quality
- for each spectral range an appropriate antireflection-coating (AR-coating) is needed for all optical elements
- for wavelengths above 1000 nm the internal transmission losses of the optical elements have to be considered. Fig. 10 shows an example of transmission losses in quartz glass. Significant transmission losses are observed at 1380 nm and above 2200 nm, which is mainly caused by water absorption (OH-stretching). Similar transmission losses are observed in other materials, like N-BK7 or materials with high refractive index that are commonly used for microoptical elements
- the alignment of optics becomes difficult because standard detection systems will not work in all spectral regions

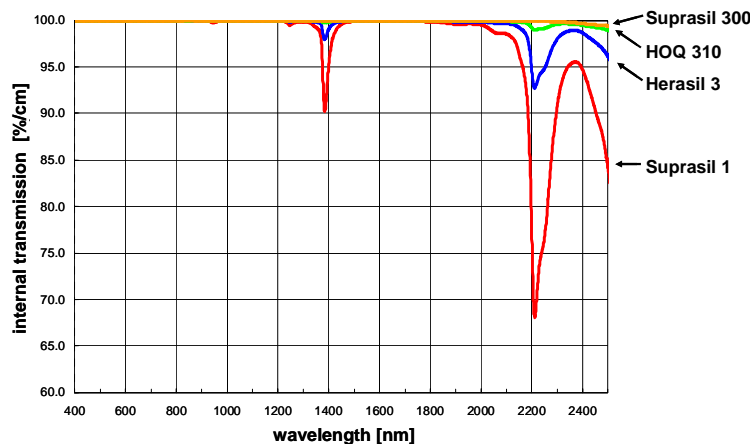


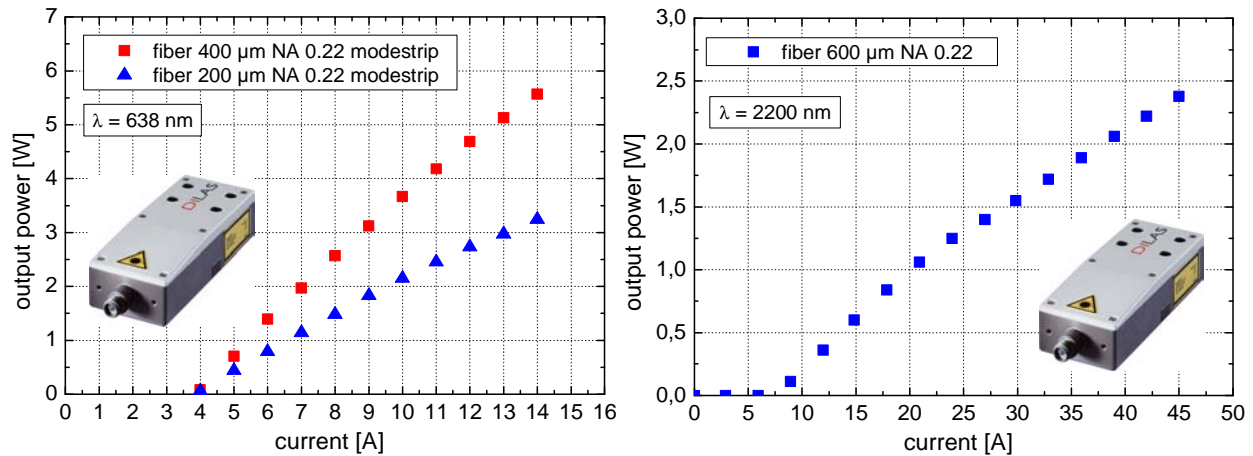
Fig. 10: Internal transmission of different quartz materials as a function of wavelength<sup>4</sup>.

## 4.2 Examples for fiber coupled diode laser modules with non-standard wavelengths

In this section different examples of fiber coupled diode laser modules with wavelengths from 638 nm up to 2200 nm are presented. All modules are based on diode laser bars mounted on passively cooled heatsinks with microoptical elements for collimation of the beam in fast- and slow-axis direction. For some modules additional microoptical elements for beam symmetrization have been used. The design considerations of section 4.1 have been taken into account to build efficient modules.

The first example is a fiber coupled single bar module at a wavelength of 638 nm. The maximum output power for this module was 5.6 W at a current of 14 A, when using a fiber with a core diameter of 400  $\mu\text{m}$  and a numerical aperture of 0.22. With a 200  $\mu\text{m}$  NA 0.22 fiber an output power of 3.2 W could be achieved. The measurement data are shown in the left diagram of Fig. 11. The right diagram of Fig. 11 shows the results for a fiber coupled single bar module at 2200 nm. The maximum output power with a 600  $\mu\text{m}$  NA 0.22 fiber was 2.4 W at a current of 45 A.

Power scaling is realized by using multiple bar modules, which can be combined by optical stacking and polarization coupling. The number of bars that can be stacked depends on the individual beam quality. As the beam quality decreases with increasing wavelength, the number of bars that can be stacked also decreases or - alternatively - the fiber diameter has to be increased. Fig. 12 shows the results of different multiple bar modules from 638 nm to 1940 nm. Table 3 summarizes typical data of diode laser modules that already have been realized.



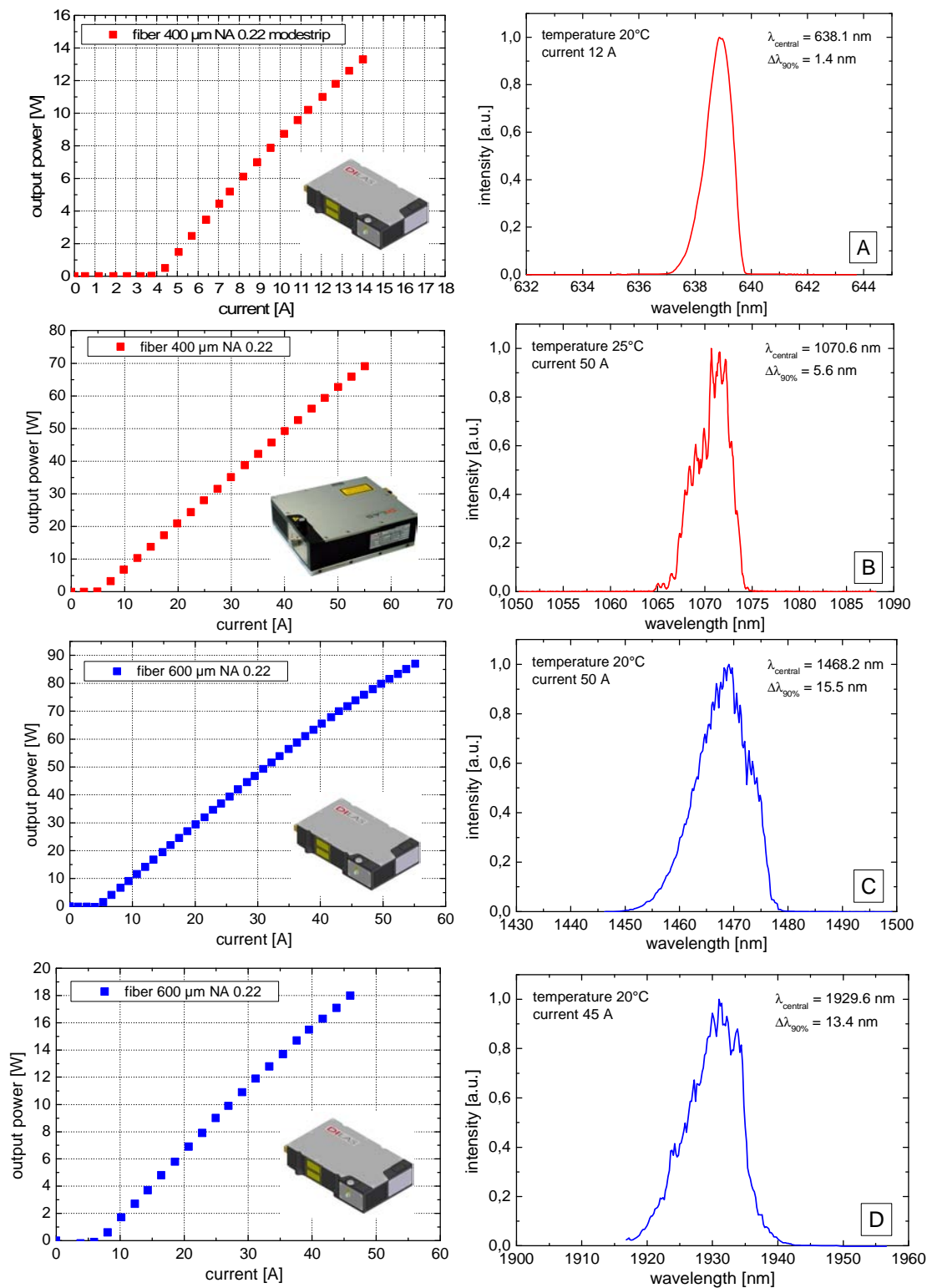
**Fig. 11:** Examples for fiber coupled single bar modules with two different wavelengths of 638 nm (left diagram) and 2200 nm (right diagram). The fiber diameters are 200  $\mu\text{m}$  and 400  $\mu\text{m}$  for 638 nm and 600  $\mu\text{m}$  for the 2200 m module each with a numerical aperture of 0.22.

Fig. 12 (A) shows the results for a module with two diode laser bars at 638 nm. The maximum output power for the two-bar module and a 400  $\mu\text{m}$  NA 0.22 fiber was 13.3 W at a current of 14 A. The corresponding spectrum was centered at 638.1 nm with a spectral width of only 1.4 nm. Another example for a two-bar module is shown in Fig. 12 (B). At a wavelength of 1070 nm as much as 69 W have been realized at a current of 55 A, when coupling the beam into a 400  $\mu\text{m}$  fiber.

At a wavelength of 1470 nm we have realized a 6-bar module with an output power of 87 W at a current of 55 A. The data are shown in Fig. 12 (C) for a 600  $\mu\text{m}$  fiber with NA 0.22. Fig. 12 (D) shows the power vs. current curve for a module with three diode laser bars at a wavelength of 1930 nm. The output power was 18 W at a current of 46 A. Power scaling could be achieved by increasing the current to 60 A (cf. Fig. 8), using an additional bar in the optical stack and by taking advantage of polarization coupling. With all these measures an output power of more than 50 W at a wavelength of about 1940 nm should be possible.

**Table 3:** Typical data of fiber coupled diode laser modules with non standard wavelengths from 638 nm up to 2200 nm. Measurement data for some of these modules are shown in Fig. 11 and Fig. 12.

	number of bars	fiber NA 0.22	output power ex fiber [W]
638 nm	1	400 $\mu\text{m}$ MS	5.5
	1	200 $\mu\text{m}$ MS	3.2
	2	400 $\mu\text{m}$ MS	13
650 nm	1	400/480 $\mu\text{m}$	5
670 nm	1	400/480 $\mu\text{m}$	12
1064 nm	1	400/480 $\mu\text{m}$	35
	2	400/480 $\mu\text{m}$	65
1210 nm	1	400/480 $\mu\text{m}$	13
1470 - 1550 nm	1	400/480 $\mu\text{m}$	15
	2	400/480 $\mu\text{m}$	30
	3	600/660 $\mu\text{m}$	45
	6	600/660 $\mu\text{m}$	90
1940 nm	1	600/660 $\mu\text{m}$	6
	2	600/660 $\mu\text{m}$	12
	3	600/660 $\mu\text{m}$	18
2200 nm	1	600/660 $\mu\text{m}$	2.2



**Fig. 12** : Power vs. current curves for different multiple bar modules with wavelengths of 638 nm (A), 1070 nm (B), 1470 nm (C) and 1940 nm (D). The right diagrams show the corresponding spectral distributions. All modules are based on diode laser bars mounted on passively cooled heatsinks.

## 5 APPLICATION

The developments described in the previous sections have been driven by the needs of the application, but technical improvements have also pushed high-power diode lasers into new markets. Some examples of new applications are :

- **630 - 680 nm :**
  - Optical pumping of  $\text{Cr}^{3+}$ -LiCAF /  $\text{Cr}^{3+}$ -LiSAF
  - Holographic applications
  - Illumination and display. However, to make high-power diode laser bars attractive for display applications the beam quality of the bars has to be improved
  - Photodynamic therapy (PDT) :  
with high power diode laser modules available in the range of 632, 635 and 652 nm, it is no longer necessary to couple dozens of single emitters together, which results in more compact devices with smaller fiber diameters
  
- **1300 – 1600 nm :**
  - This wavelength region is important because of water absorption maximum in tissue at 1450 nm, minimization of optical fiber attenuation and free space optical attenuation as well as human eye absorption of light at the cornea for wavelengths  $> 1350$  nm (so-called eye-safe), which protects the retina against focused damage ( $< 1100$  nm)
  - Dermatological aesthetic medical treatments like wrinkle reduction and scar removal
  - Optical pumping of  $\text{Er}^{3+}$ :YAG at 1530 nm
  - Eye-safe military applications for targeting and guidance systems  $> 1350$  nm
  - Free space optical transmissions
  - Especially for applications in the medical device manufacturing, white polymers and transparent polymers are of high interest. In this branch the usage of special additives is not recommended because of the tedious approval procedures. Therefore, solutions are needed which definitely work without any additives, respectively will work with the material combinations which are already approved and used. For welding of white polymers the use of longer wavelengths, e.g. in the range of 1470 nm, allows a better usage of plastics with a better white color impression. The welding at 1470 nm benefits from the fact that the approved substances used for the white color impression can be varied in concentration to allow “laser-transparent” and “laser-absorbing” properties at 1470 nm without influence on the white appearance in the visible.
  
- **$> 1800$  nm :**
  - Welding of transparent plastics :  
For transparent plastics the welding principle is completely different. Without additives such plastics normally do not absorb light from the visible range, even up to 1550 nm. Yet, there is a chance to use the intrinsic absorption of polymers, starting at a wavelength of approximately 1800 nm. The intrinsic absorption is caused by the vibrations of the polymer chains under influence of the light  $> 1800$  nm. In contrast to laser sources around  $1 \mu\text{m}$  the laser beam at  $> 1.8 \mu\text{m}$  is absorbed by the chemical bonds of the thermoplastic material itself. This is ideal for medical device manufacturing, as transparent polymers can be welded without using additives or absorbing intermediate layers. As the process happens in the bulk material and not at the surface, this is well-suited for foil welding or tube welding, resulting in a through-welding process<sup>5</sup>
  - Medical applications in laser surgery and therapy due to the absorption characteristics of water and biological tissues containing water. For example, the water absorption of human tissue at 1940 nm is about three orders of magnitude larger than at 980 nm.
  - Optical pump sources for laser systems emitting in the 2 – 4  $\mu\text{m}$  wavelength range
  - Military applications such as infrared countermeasures

## 6 SUMMARY AND OUTLOOK

In conclusion, we have demonstrated efficient and stable operation of high-power diode laser bars with emission wavelengths from 410 nm to 2200 nm. For this large wavelength range different semiconductor material compositions have to be used. We have shown detailed results for (InGaN)(GaN)-diode laser bars around 410 nm, (InGaAlP)(GaAs)-bars from 630–675 nm, (InGaAs)(GaAs)-bars at 1070 nm, (InGaAsP)(InP)-bars from 1380–1550 nm and (AlGaIn-AsSb) (GaSb)-bars with wavelengths above 1800 nm.

The achievable output power strongly depends on the wavelengths of the diode laser bar. Among other results we have demonstrated 12 W at a wavelength of 415 nm, 7.8 W at 638 nm, 28 W at 675 nm, 80 W at 1070 nm, 35 W at 1470 nm, 15 W at 1940 nm and 9.6 W at 2200 nm. All these results were achieved with single diode laser bars mounted on a passively cooled heatsink and operating in continuous-wave mode. In addition, we have shown lifetime tests for a couple of different bars with a runtime of up to 7000 h for diode laser bars at 1940 nm.

For most of the applications fiber coupled modules are required. We have pointed out the key issues that have to be considered for building efficient modules in different wavelength ranges. Based on the results of the diode laser bars we have built single and multiple bar diode laser modules with wavelengths from 638 nm up to 2200 nm. Fiber coupling of these modules resulted in an output power of 13.3 W at 638 nm and 69 W at 1070 nm with a 400  $\mu\text{m}$  fiber with numerical aperture of 0.22. For longer wavelengths modules with 87 W at 1470 nm and 18 W at 1940 nm have been realized with 600  $\mu\text{m}$  fibers (NA 0.22). Finally we have given a short summary of applications for such modules with non-standard wavelengths.

In summary the results show that diode laser modules with non-standard wavelengths are very attractive light sources that find many applications in various fields. For a lot of these newer wavelengths, work is ongoing to improve the materials, processes and structures, and even better results can be expected in the near future.

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