Diode laser arrays for 1.8 to 2.3 µm wavelength range

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ABSTRACT

High-power diode lasers in the mid-infrared wavelength range between 1.8µm and 2.3µm have emerged new possibilities either for direct military applications or as efficient pump sources for laser sources in the 2-4µm wavelength range for infrared countermeasures. GaSb based diode lasers are naturally predestinated for this wavelength range and offer clear advantages in comparison to InP based diode lasers in terms of output power and wall-plug efficiency.

We will present results on different MBE grown (AlGaIn)(AsSb) quantum-well diode laser single emitters and linear laser arrays, the latter consisting of 19 emitters on a 1cm long bar, emitting at different wavelengths between 1.8µm and 2.3µm. Single emitters have resonator lengths between 1.0 and 1.5mm and stripe widths between 90µm and 200µm. Laser bars with 20% and 30% fill factors have been processed. For single emitters the electro-optical behaviour, beam quality and wavelength tunability have been investigated in detail. For diode laser bars mounted either on actively or passively cooled heat sinks by Indium or AuSn solder, more than 20W at 1.9µm in continuous-wave mode have been achieved at a heat sink temperature of 20°C resulting in maximum wall-plug efficiencies of 30%. Even at 2.2µm more than 16W have been measured, impressively demonstrating the potential of GaSb based diode lasers well beyond wavelengths of 2µm. Application driven fiber coupled single emitter based modules with 600mW as well as fiber coupled bar based modules with 20W have been realized.

Keywords: diode laser arrays, laser bars, GaSb diode laser, mid-infrared laser, infrared countermeasure, pump laser

1. INTRODUCTION

High power diode lasers emitting at wavelengths between 1850 nm and 2300 nm open up a wide range of applications as compact and efficient light sources in the fields of infrared countermeasures (IRCM), pumping of solid state[1-2] and optically pumped semiconductor lasers[3] emitting in the 2-4µm regime, low probability of intercept communication links, and trace gas analysis. Civilian applications exist in the fields of laser surgery[4], medical diagnostics[4] and dermatological treatments[4] as well as direct materials processing such as plastics or aqueous varnish processing[5]. For all these applications output powers in the Multiwatt range, long lifetimes, a low-cost packaging technology and fiber coupling are preferable for practical purposes.

GaSb based Quantum Well (QW) diode lasers fabricated using the GaSb based (AlGaIn)(AsSb) materials system are naturally predestined for this wavelength range[6-9] and offer clear advantages in comparison to InP based diode lasers in terms of output power and wall-plug efficiency. In this paper, we will present results on high output power (AlGaIn)(AsSb) quantum-well diode laser single emitters as well as linear arrays consisting of 19 emitters on a 1cm long bar. The emitting wavelengths are 1870nm, 1908nm 1930nm and 2210nm. Based on these single emitters and laser bars, fiber coupled modules will be presented with up to 20W out of a 600µm core fiber. In the next section a short introduction into the fabrication of GaSb based diode lasers will be given.

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2. LASER STRUCTURE AND PACKAGING

The laser structure used here was grown on (100)-oriented 2-inch n-type GaSb:Te substrates by solid-source molecular beam epitaxy[7-11]. The active region consists of three 10 nm wide GaInSb QWs with Ga and In concentrations according to the targeted wavelength. The QWs are separated by 20 nm wide lattice matched $Al_{0.30}Ga_{0.70}As_{0.03}Sb_{0.97}$ barrier layers. We have used a narrow waveguide core with a width of each $Al_{0.30}Ga_{0.70}As_{0.03}Sb_{0.97}$ SC layer of only 120nm. The waveguide core is embedded between 2µm wide lattice matched $Al_{0.50}Ga_{0.50}As_{0.04}Sb_{0.96}$ n- and p-doped cladding layers.

From these epitaxial layer structures 150µm as well as 90µm wide gain-guided broad-area lasers were fabricated using standard optical lithography in combination with dry etching techniques for lateral patterning, and lift-off metallization for p-contact formation. Backside processing started with substrate thinning followed by the deposition of the n-contact metallization and annealing. Part of the wafers were chipped into single emitters with different resonator lengths (1.0-1.5mm) and stripe widths (90-200µm). The devices were mounted junction side down either by Indium or AuSn solder on gold-coated copper heat sinks (C-mounts). The rear facets are coated with a highly reflective double-stack of Si and SiO_2 films (> 95% reflectivity) and the front facets are coated by a single layer of SiN (3% reflectivity). Uniform pumping of the laser diodes is achieved by current injection using evenly spread bond wires.

In addition linear broad-area laser arrays with 19 emitters on a 1cm long bar were fabricated. The bars were In- or AuSn soldered epi-side down onto passively or actively cooled gold-coated copper heat sinks. The temperature management has been done by heat exchange with a water-cooled bar holder. Uniform pumping of the laser arrays is achieved by current injection using a copper top cover.

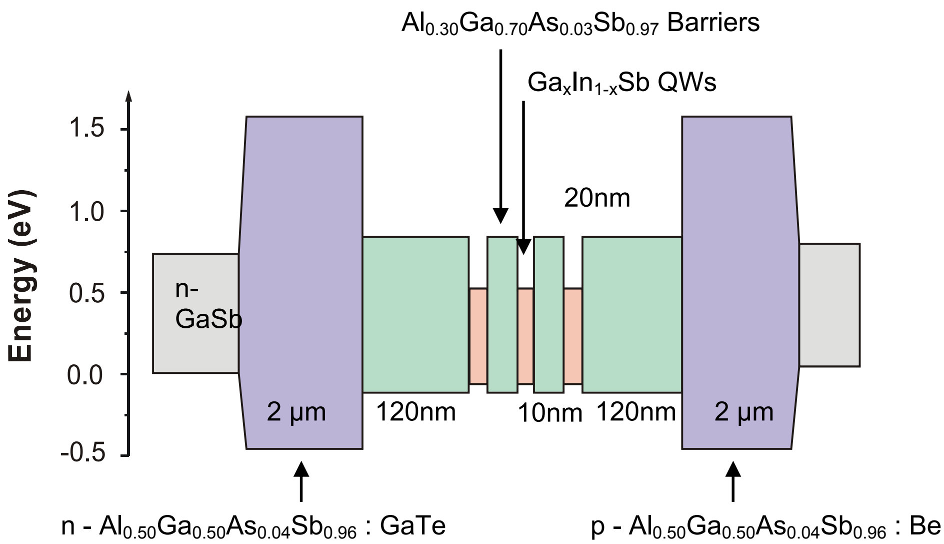

Figure 1. Layer design of GaSb based high-power broad-area diode lasers. The laser structures have been grown on 2-inch n-type GaSb:Te substrates.

3. SINGLE EMITTER PERFORMANCE

Figure 2 shows the output power-vs.-current characteristics and the current dependent wall-plug efficiency of broad-area single emitters at different wavelengths and different stripe widths. Table 1 gives an overview of the electro-optical characteristics. For all wavelengths and emitter designs, the slope efficiencies are >0.3 W/A and except the single emitters at 2210 nm all wall plug efficiencies are well above 25%. At 1940nm we have achieved even 30% wall-plug efficiency due to the reduced voltage by the selected emitter size. For 2210 nm the wall-plug efficiency slightly decreases

due to an increased operation voltage. This leads to an output power of 1±0.1 W at 4 A for all different wavelengths. Values for the threshold currents are between 0.28A and 0.38A between 1870 nm and 2210 nm.
The measured far field distribution ($1/e^2$ definition) in the slow and in the fast axis is shown in figure 3 for a 150 x 1000 μm^2 and a 90 x 1500 μm^2 single emitter. The slow axis far fields show a strong dependence on the current density due to significant self-heating of the devices as a result of the lower wall-plug efficiency (e.g. in comparison to GaAs based high-power diode lasers) and thus increased heat dissipation. For fiber coupling a smaller stripe width such as 90 µm will be more preferable, but a smaller stripe width is connected with a wider far field typically. In the case of GaSb based diode lasers, heat dissipation plays an important role and therefore by increasing the resonator length to 1500 µm it was possible to design a diode laser with a decreased stripe width of 90 µm and the same slow axis far field as a 150 µm wide broad-area diode laser. The fast axis far fields show current independent values of 79° in $1/e^2$ definition or 44° FWHM and enable the use of standard optics and efficient coupling to fibres.

emitting wavelength (nm)	1870	1908	1940	2210
stripe width (µm)	90	150	200	150
resonator length (µm)	1500	1500	1000	1000
I_{th} (A/cm^2)	0.38	0.28	0.37	0.33
s.e. (W/A)	0.31	0.33	0.35	0.30
η_{max} (%)	27.4	26.5	30.0	20.6
output power @ 4A (W)	0.97	1.17	1.15	0.9

Table 1. Overview of electro-optical characteristics of different broad-area single emitters. The data have been measured at a heat sink temperature of 20 °C and continuous wave (cw) operation.

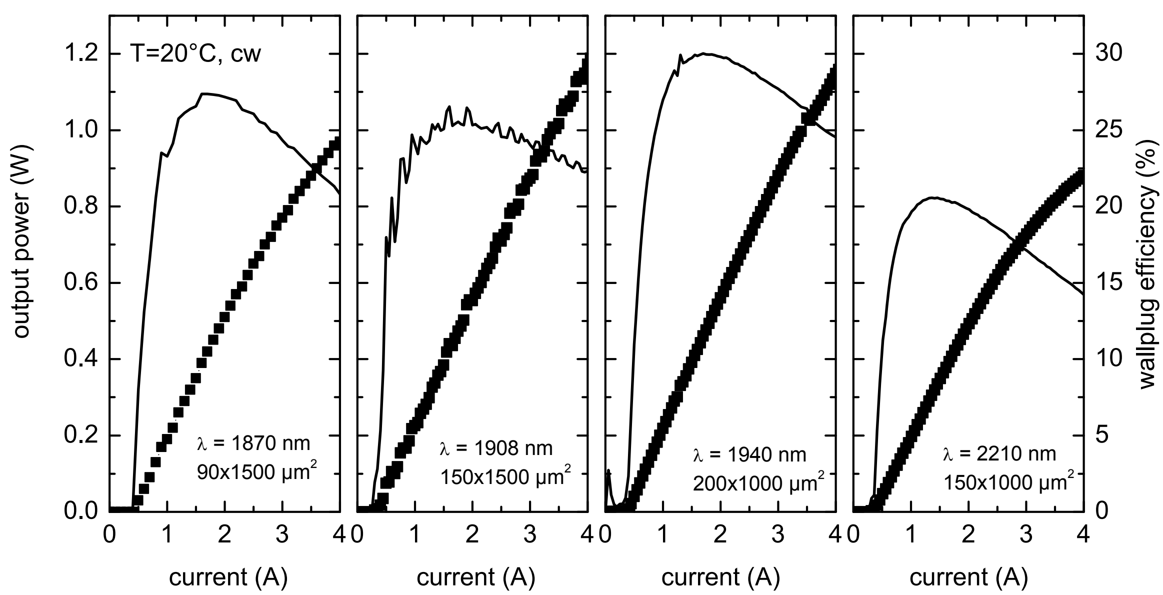

Figure 2. Output power-vs.-current characteristics and current dependent wall-plug efficiencies of different broad-area single emitters. The measurements have been carried out at a heat sink temperature of 20 °C in continuous wave mode (cw). Table 1 gives an overview of the electro-optical characteristics.

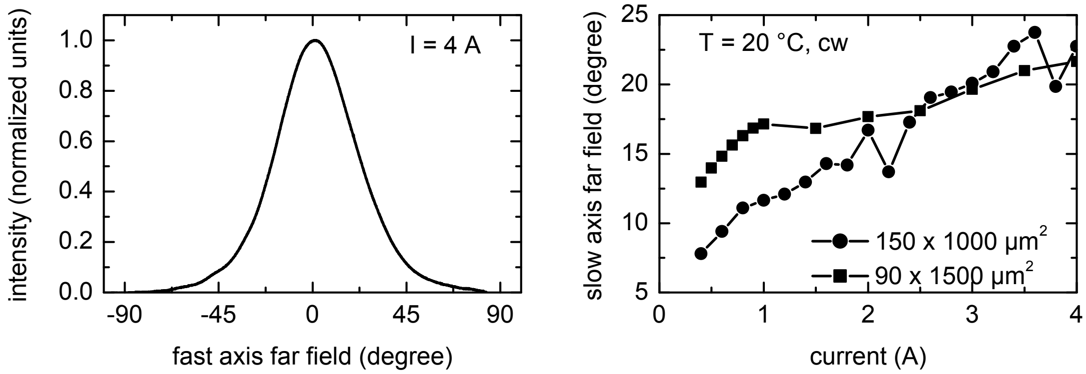

Figure 3. Slow axis and fast axis far fields of a 1000 x 150 µm^2 and a 1500 x 90 µm^2 single emitter at 1940 nm.

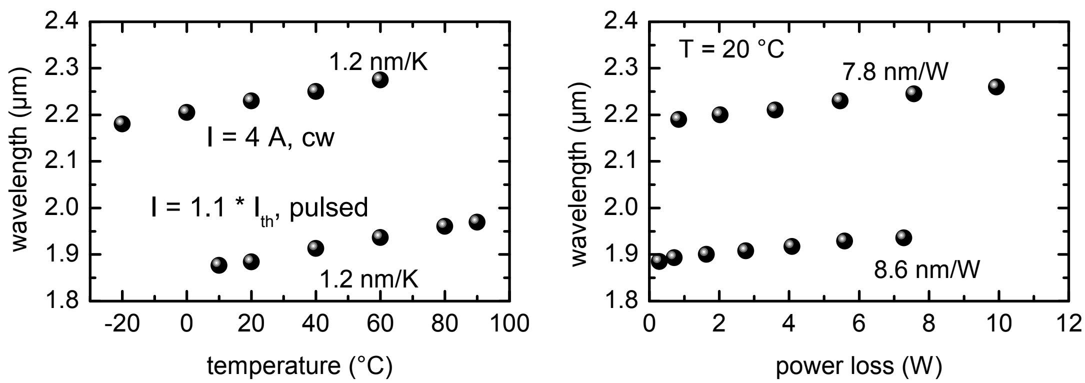

Figure 4. Dependence of the peak emission wavelength on temperature (left side) and power dissipation (right side) for 1000 x 150 µm^2 single emitters at 1870 nm and 2210 nm.

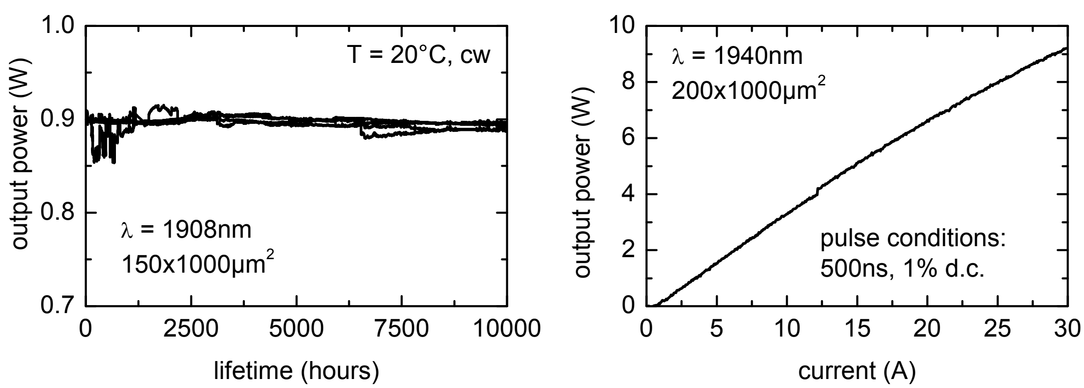

Figure 5. (left hand side) CW output power vs. time for a set of 4 emitters. The measurements have been performed at a heat sink temperature of 20°C in cw operation. (right hand side) Pulsed output power vs. current for a single emitter at 1940 nm.

In figure 4 the shifts of the emission wavelength of 1000x150µm^2 single emitters at 1850nm and 2210nm with temperature (1.2nm/K) and as a function of dissipated power (7.1 +/- 0.7nm/W) are given. Whereas the wavelength shift with power loss has been measured in cw operation, the emission wavelength as a function of temperature has been measured both in high-power cw operation at a constant current of 4A and, to avoid self-heating effects, also in pulsed mode 10% above threshold current.

The long-term reliability of these diode lasers has been tested by aging some devices at a heat sink temperature of 20°C (figure 5). The batch of four devices has been tested under constant current condition at 3 A. The initial output power is about 0.9W. All devices show only gradual degradation even after 10.000 hours of continuous operation. To test for COMD effects, for a 1000x200µm^2 single emitter at 1940nm the operation current has been ramped up to 30A. No sudden failure has been detected.

4. DIODE LASER ARRAY PERFORMANCE

Linear arrays of 19 broad area emitters with a strip width of 150µm (30% fill factor) or 90µm (20% fill factor) and a centre-to-centre spacing between the individual laser strips of 500µm have been fabricated and AuSn or In-soldered p-side down on passively and actively cooled heat sinks. The resonator length of the lasers was 1000µm for the 30% fill factor bars and 1500nm for the 20% fill factor bars. Table 2 gives an overview of the electro-optical characteristics of 1908nm, 1940nm and 2210nm laser bars and together with fig. 4 a comparison of 20% and 30% fill factor bars at 1940m. For an actively cooled 1908nm laser array with 30% fill factor a maximum output power of 19.5W at 68A has been achieved (figure 7).

A maximum cw power of 16 W has been demonstrated at 75A for a 19 emitter array emitting at 2200nm (figure 7), only limited by thermal rollover and not by a COMD. The saturation of the current-power curve at higher currents is caused by array heating. A high maximum wall-plug efficiency of more than 23% has been measured at 30A for an array emitting at 2200nm. This is to our knowledge the highest cw output power and wall-plug efficiency of a diode laser array emitting above 2µm ever reported.

The long-term reliability of these laser bars has been tested by aging some devices at a heat sink temperature of 21°C (figure 8). The batch of four bars has been tested under constant current condition at an initial output power of 10W. After 3100 hours laser bars have been controlled by a P-I-U measurement and again started, but this time at 14 W initial output power. Tests are ongoing.

emitting wavelength (nm)	1908	1940	1940	2200
number of emitters	20	19	19	19
emitter design (µm)	150 x 1000	150 x 1000	90 x 1500	150 x 1000
fill factor	30%	30%	20%	30%
heat sink	active	passive	passive	passive
heat sink temperature (°C)	20	20	20	17
I_{th} (A)	10	5.1	6.0	7.05
s.e. (W/A)	0.28	0.28	0.34	0.30
η_{max} (%)	25	29	26	23
operation current @ 10W (A)	36	41	37	41

Table 2. Overview of electro-optical characteristics of different broad-area laser arrays. The data have been measured at a heat sink temperature of 25 °C and continuous wave (cw) operation.

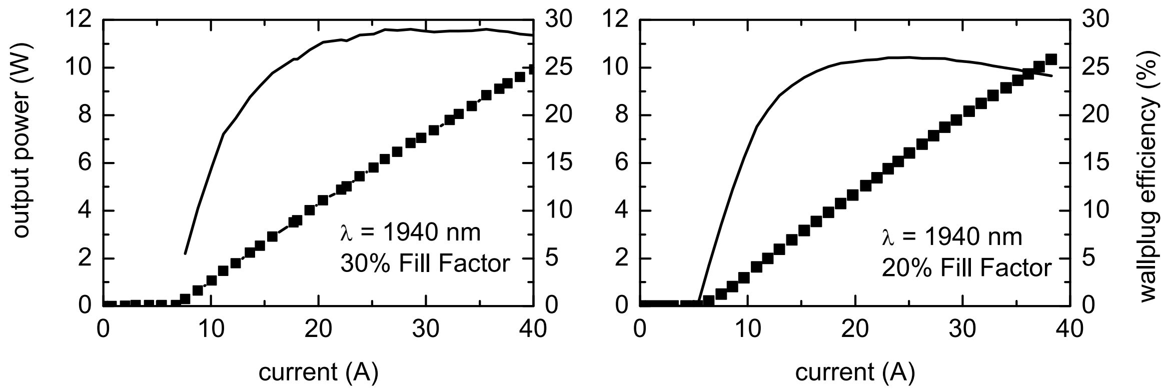

Figure 6. Output power-vs.-current characteristic of diode laser arrays with 20% and 30% fill factor emitting at 1940 nm and mounted on passively cooled heat sinks. The measurements have been carried out at a heat sink temperature of 25 °C in CW operation.

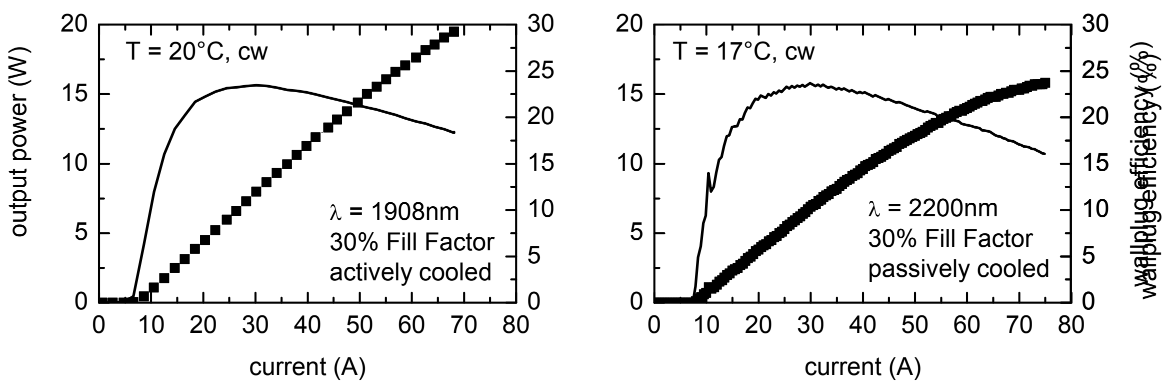

Figure 7. CW output power vs. current characteristics recorded for diode laser arrays emitting at 1940 nm and 2200 nm.

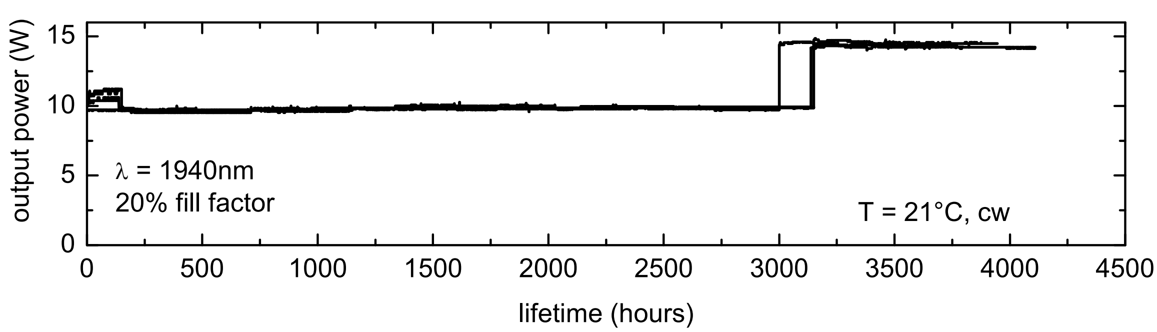

Figure 8. CW output power vs. time for a set of 4 laser bars. The measurements have been performed at a heat sink temperature of 21 °C in cw operation.

5. LASER MODULES

The diode laser single emitters and laser arrays are suitable for fiber coupling. In fig. 9 broad-area single emitters with $150x1000\mu m^2$ design emitting at 1930nm and 2210nm have been coupled into 200µm core fibers (NA=0.22). At 1870nm maximum peak power ex fiber was 290mW corresponding to a coupling efficiency of 75%. At lower output powers coupling efficiency is in the range of 85%. For 2210nm a maximum peak power ex fiber of 230mW has been demonstrated, corresponding to a coupling efficiency of 85%.

Fig. 10 shows the results for fiber coupled laser arrays at 1940nm. For a 1-bar module a maximum peak power ex fiber of 7.4W has been established for a 400 µm core fiber (70% coupling efficiency). Taking an 800 µm core fiber 8.7W ex fiber has been demonstrated (80% coupling efficiency. Several laser arrays can be coupled to achieve even higher output powers. For a 3-bar module a peak power of 20W has been measured out of a 600µm core fiber with NA 0.22.

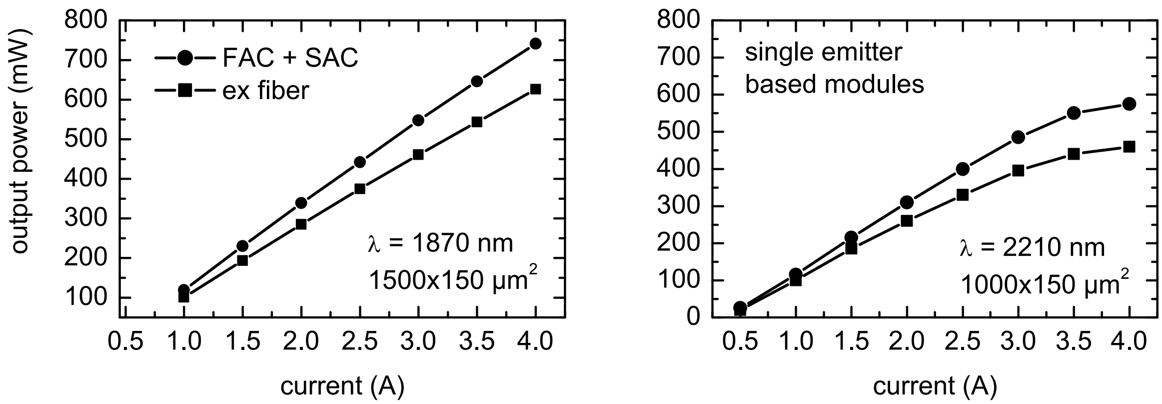

Figure 9. CW output power vs. current characteristics for different fiber coupled single emitter based modules emitting at 1940nm and 2210 nm. All measurements have been performed at 20 °C heat sink temperature.

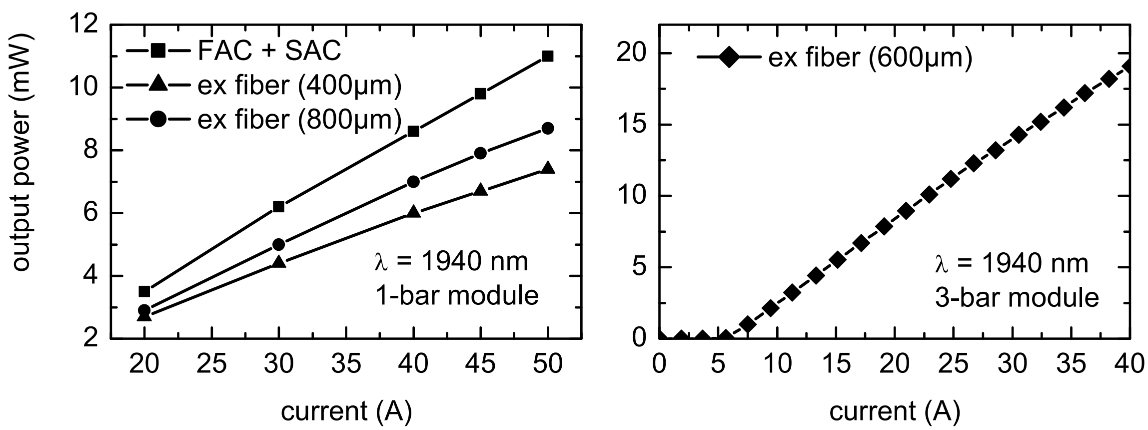

Figure 10. CW output power vs. current characteristics for different fiber coupled bar based modules emitting at 1940nm. All measurements have been performed at 20°C heat sink temperature.

6. CONCLUSION

Recent advances in high-power (AlGaIn)(AsSb) based diode lasers in the 2 µm spectral range have been reported. These diodes are favorable as compact and efficient light sources either for military or civilian applications.

High power diode lasers at 1870nm, 1908nm, 1940 nm and 2210 nm with 1W of output power have been reported. 20 W in continuous-wave mode at a heat sink temperature of 20°C have been achieved for linear arrays with 19 emitters at 1908nm, which show the same high maximum wall-plug efficiency of more than 26% as the single emitters. These output powers are among the highest reported so far for GaSb based diode lasers. For a passively cooled laser array at 2200nm a wall-plug efficiency of 23% has been reported. This is to our knowledge the highest cw wall-plug efficiency of a diode laser array emitting above 2µm ever reported.

Future directions for R&D in the field of high-power (AlGaIn)(AsSb) based laser arrays will have to include studies for pulse operation both on single emitters and on linear diode arrays. Another issue to be addressed with respect to reduced prices for (AlGaIn)(AsSb) diode laser arrays is the GaSb substrate size. So far all reported III-Sb based diode lasers have been grown exclusively on 2-inch n-type GaSb:Te substrates. However, to fabricate linear diode laser arrays more cost-effectively, the size of the available substrates should be increased to at least 3-inch diameter.

7. ACKNOWLEDGEMENT

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