High-power diode lasers for the 1.9 to 2.2 µm wavelength range

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ABSTRACT

GaSb based diode laser both as single emitters and as linear arrays, emitting between 1.9 and 2.2 µm, have a huge potential especially for materials processing, medical applications and as optical pump sources for solid state laser systems emitting in the 2-4 µm wavelength range. Determined by the absorption characteristics of thermoplastic materials at wavelengths around 2 µm, the light emitted by the diode laser will be absorbed by the material itself and can thus be used for marking and welding without the addition of e.g. colour pigments.

We will present results on different (AlGaIn)(AsSb) quantum-well diode laser single emitters and linear laser arrays, the latter consisting of 20 emitters on a 1 cm long bar, emitting at different wavelengths between 1.9 and 2.2 µm. To improve on the typically poor fast axis beam divergence of diode lasers emitting at these wavelengths, we abandoned the broadened waveguide concept and changed over to a new waveguide design which features a rather narrow waveguide core. This results in a remarkable reduction in fast axis beam divergence to 43° FWHM for the new waveguide design. Electro-optical and thermal behaviour and the wavelength tunability by current and temperature have been carefully investigated in detail. For single emitters cw output powers of 2 W have been demonstrated. For diode laser arrays mounted on actively cooled heat sinks, more than 20 W in continuous-wave mode have been achieved at a heat sink temperature of 20 °C resulting in wall-plug efficiencies of more than 26%.

Keywords: diode laser arrays, laser bars, GaSb diode laser, 2 µm, material processing, thermoplastic material

1. INTRODUCTION

High power diode lasers emitting at wavelengths around 2 µm have significant potential as compact and efficient light sources in the fields of laser surgery and therapy as well as direct materials processing. In contrast to GaAs based diode lasers or Nd:YAG lasers emitting in the wavelength regime around 1 µm which are not well suited for the processing of transparent thermoplastic materials, the energy of the laser beam at 2 µm is directly absorbed in the thermoplastic material by intrinsic vibrational modes. The absorption of laser radiation at this wavelength in the volume of the material results in a direct and immediate heating and melting. Therefore the addition of colour pigments or other additives is not necessary. This offers great benefits for example in the field of processing transparent plastic in the packaging industry¹. There is also a sizeable potential for the application of these lasers in laser surgery and therapy due to the absorption characteristics of water and biological tissues containing water at wavelengths around 2 µm². In addition, optical pump sources for laser systems emitting in the 2-4 µm wavelength range and defence related applications, such as infrared countermeasures, are addressed³-⁵. 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. Quantum well (QW) diode lasers fabricated using the GaSb based (AlGaIn)(AsSb) materials system allow to cover this wavelength range⁶-⁸.

A serious drawback of the large optical cavity (LOC) design used so far for state-of-the-art GaSb based broad-area lasers⁹-¹⁰ is a large fast axis beam divergence with a FWHM of typically 63° to 67°. Therefore we have abandoned the broadened waveguide concept and changed over to a vertical waveguide design which features a rather narrow waveguide core and a reduced refractive index step between waveguide and cladding section. Within this concept we have realized high-power diode lasers with vertical far fields of less than 45° FWHM¹¹,¹². 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 20 emitters on a 1 cm long bar. The emitting wavelengths are 1.908 µm, 1.93 µm and 2.2 µm.
The laser structure used here was grown on (100)-oriented 2-inch n-type GaSb:Te substrates by solid-source molecular beam epitaxy\textsuperscript{1-15}. The active region consists of three 10 nm wide GaInSb QWs with Ga and In concentrations according to the targeted wavelength (example: Ga\textsubscript{0.83}In\textsubscript{0.17}Sb results in 1908 nm lasers). The QWs are separated by 20 nm wide lattice matched Al\textsubscript{0.30}Ga\textsubscript{0.70}As\textsubscript{0.03}Sb\textsubscript{0.97} barrier layers. We have used a narrow waveguide core with a width of each Al\textsubscript{0.30}Ga\textsubscript{0.70}As\textsubscript{0.03}Sb\textsubscript{0.97} SC layer of only 120 nm. The waveguide core is embedded between 2 \( \mu \)m wide lattice matched Al\textsubscript{0.50}Ga\textsubscript{0.50}As\textsubscript{0.04}Sb\textsubscript{0.96} n- and p-doped cladding layers. This waveguide design yields in comparison to the LOC design a larger confinement factor with the doped cladding layers, which was compensated by appropriate adjustments of the doping profile. As the internal losses are dominated by the absorption due to free carriers in the p-cladding, the Be-doping in the inner part of the p-cladding was reduced in order to keep the internal losses at least as low as the LOC design.

From these epitaxial layer structures 150 \( \mu \)m as well as 90 \( \mu \)m 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 1000 x 150 \( \mu \)m\textsuperscript{2} and 1500 x 90 \( \mu \)m\textsuperscript{2} single emitters. The devices were mounted junction side down on gold-coated copper heat sinks (C-mounts). The rear facets are coated with a highly reflective double-stack of Si and SiO\textsubscript{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 20 emitters on a 1 cm long bar were fabricated. The 150 \( \mu \)m wide emitters were arranged with a 500 \( \mu \)m center-to-center pitch. The bars were In-soldered epi-side down onto passively and 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.

![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.](image-url)
3. SINGLE EMITTERS

Figures 2 and 3 show 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 the single emitter at 1908 nm the operation current has been ramped up to a current of 8 A resulting in an output power of 1.96 W. Slope efficiency of 0.33 W/A and a maximum wall-plug efficiency of 26.5% are remarkable results for the GaSb based material system.

<table>
<thead>
<tr>
<th>emitting wavelength (nm)</th>
<th>1908</th>
<th>1930</th>
<th>1930</th>
<th>2200</th>
</tr>
</thead>
<tbody>
<tr>
<td>emitter width (µm)</td>
<td>150</td>
<td>150</td>
<td>90</td>
<td>150</td>
</tr>
<tr>
<td>resonator length (µm)</td>
<td>1000</td>
<td>1000</td>
<td>1500</td>
<td>1000</td>
</tr>
<tr>
<td>I_{th} (mA)</td>
<td>320</td>
<td>390</td>
<td>480</td>
<td>350</td>
</tr>
<tr>
<td>s.e. (W/A)</td>
<td>0.33</td>
<td>0.33</td>
<td>0.37</td>
<td>0.29</td>
</tr>
<tr>
<td>(\eta_{\text{max}}) (%)</td>
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<td>25.2</td>
<td>24.2</td>
<td>20.0</td>
</tr>
<tr>
<td>output power @ 4A (W)</td>
<td>1.17</td>
<td>1.15</td>
<td>1.15</td>
<td>0.98</td>
</tr>
</tbody>
</table>

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](image-url)  

Figure 2. Output power-vs.-current characteristics and current dependent wall-plug efficiencies of a 150 x 1000 µm² broad-area single emitter at 1908 nm at a heat sink temperature of 20 °C measured in continuous wave mode (cw).

The measured far field distribution (1/e² definition) in the slow and in the fast axis is shown in figure 4 for a 150 x 1000 µm² single emitter. The slow axis far field shows a strong dependence on the current density due to significant self-heating of the device 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 the fast axis far field there is a remarkable reduction (FWHM: 44°, 1/e²: 79°) in fast axis beam divergence as compared to state-of-the-art GaSb based LOC lasers. The values are current independent. This strong decrease in the fast axis divergence will drastically increase the coupling efficiency of the laser light into an optical setup, increasing the net efficiency of the whole system.
Figure 3. 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).

In figure 5 the shifts of the emission wavelength of 1000 150 µm² single emitters at 1908 nm and 2200 nm with temperature (1.2 nm/K) and as a function of dissipated power (7.1 +/- 0.7 nm/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 4 A and, to avoid self-heating effects, also in pulsed mode 10% above threshold current. From both measurements the thermal resistance of the C-mount packaging has been extracted to be 7 K/W.
The long-term reliability of these diode lasers has been tested by aging some devices at a heat sink temperature of 20 °C (figure 6). The batch of five LOC-devices has been tested under constant current condition at 3 A. The initial output power is about 0.9 W. All devices show only gradual degradation even after 10,000 hours of continuous operation with only one device failing prematurely after 4000 hours. To test for COMD effects, for a 1000 x 150 µm$^2$ single emitter at 1908 nm the operation current has been ramped up to 30 A. No sudden failure has been detected. Of course further reliability tests at higher operation currents including a larger number of devices are required and will be carried out.

Figure 5. Dependence of the peak emission wavelength on temperature (left side) and power dissipation (right side) for 1000 x 150 µm$^2$ single emitters at 1908 nm and 2200 nm.

Figure 6. (left hand side) CW output power vs. time for a set of 5 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 1908 nm. The measurement has been performed with 500 µs current pulses at 17 °C heat sink temperature.
4. DIODE LASER ARRAYS

To increase the CW output power, linear arrays of 12 and 20 broad area emitters with a strip width of 150 µm and a centre-to-centre spacing between the individual laser strips of 500 µm have been fabricated and In-soldered p-side down on passively and actively cooled heat sinks. The resonator length of the lasers was 1000 µm. Table 2 gives an overview of the electro-optical characteristics.

<table>
<thead>
<tr>
<th>emitting wavelength (nm)</th>
<th>1908</th>
<th>1908</th>
<th>1908</th>
<th>1930</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of emitters</td>
<td>12</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>emitter design (µm)</td>
<td>150 x 1000</td>
<td>150 x 1000</td>
<td>150 x 1000</td>
<td>150 x 1000</td>
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<tr>
<td>heatsink</td>
<td>passive</td>
<td>passive</td>
<td>active</td>
<td>passive</td>
</tr>
<tr>
<td>$I_\text{th}$ (A)</td>
<td>6.3</td>
<td>6.5</td>
<td>10.0</td>
<td>5.2</td>
</tr>
<tr>
<td>s.e. (W/A)</td>
<td>0.28</td>
<td>0.30</td>
<td>0.28</td>
<td>0.28</td>
</tr>
<tr>
<td>$\eta_{\text{max}}$ (%)</td>
<td>21.5</td>
<td>26.8</td>
<td>25.0</td>
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<tr>
<td>$P_{\text{max}}$ (W)</td>
<td>11.0</td>
<td>17.0</td>
<td>20.8</td>
<td>---</td>
</tr>
<tr>
<td>output power @ 40A (W)</td>
<td>8.9</td>
<td>9.3</td>
<td>8.5</td>
<td>9.9</td>
</tr>
</tbody>
</table>

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 7. Output power-vs.-current characteristic of different linear diode laser arrays emitting at 1908 nm and mounted on passively or actively cooled heat sinks. The measurements have been carried out at a heat sink temperature of 25 °C in CW operation.

The maximum cw power of 20.8 W has been achieved at 92 A for a 20 emitter array emitting at 1908 nm, only limited by thermal rollover and not by a COMD. Slope efficiencies and threshold currents are comparable to the results we have achieved with single emitters. The saturation of the current-power curve at higher currents is caused by array heating. A high maximum wall-plug efficiency of more than 29% has been measured at 8 W for an array emitting at 1930 nm. This is to our knowledge the highest cw wall-plug efficiency of a diode laser array emitting around 2 µm ever reported.
Figure 8. CW output power vs. current characteristics recorded after different operating times for a diode laser array emitting at 1930 nm. The measurements have been performed at a heat sink temperature of 25 °C in cw operation.

The long-term reliability of these diode laser arrays has been tested by operating a device for 500 hours at a heat sink temperature of 25 °C and an output power of 10 W (figure 8). Every 100 hours an output power-vs.-current characteristic has been measured, showing no sign of degradation.

5. CONCLUSION

Recent advances in high-power (AlGaIn)(AsSb) based diode lasers in the 2 µm spectral range have been reported. These diodes are favorable for applications in medical treatment, materials processing and pumping of solid state lasers.

For single emitters with narrow waveguide design a cw output power of more than 1.9 W has been achieved at 1908 nm. High power diode lasers at 1930 nm and 2200 nm with 1 W of output power have been reported for the first time. 20.8 W in continuous-wave mode at a heat sink temperature of 20 °C have been achieved for linear arrays with 20 emitters at 1908 nm, 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 1930 nm a wall-plug efficiency of 29% has been reported. This is to our knowledge the highest cw wall-plug efficiency of a diode laser array emitting around 2 µm ever reported.

Future directions for R&D in the field of high-power (AlGaIn)(AsSb) based laser arrays will have to include reliability studies both on single emitters and on linear diode arrays. Another issue to be addressed with respect to a further commercialisation of (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.

6. ACKNOWLEDGEMENT

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