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 1.8 µm and 2.3 µm have emerged new possibilities for application fields like materials processing, medical surgery and for military applications like infrared countermeasures. GaSb based diode lasers are naturally predestined 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 1 cm long bar, emitting at different wavelengths between 1.8 and 2.3 µm. Each emitter has a resonator length of 1.0 mm or 1.5 mm and stripe widths of 90 µm or 150 µm. The distance from emitter to emitter is 500µm for both types, resulting in 20% and 30% fill factors. For single emitters the electro-optical and beam behaviour and the wavelength tunability by current and temperature have been carefully investigated in detail. For diode laser arrays mounted on actively cooled heat sinks, nearly 20W at 1.94µm in continuous-wave mode have been achieved at a heat sink temperature of 20 °C. Even at 2.2µm more than 15W with a wall plug efficiency of 23% have been measured, impressively demonstrating the potential of GaSb based diode lasers well beyond wavelengths of 2µm.

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

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 laser surgery and therapy as well as direct materials processing such as plastics or aqueous varnish 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 industry. 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 µm⁻¹. 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 addressed². 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 range³ 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 1 cm long bar. The emitting wavelengths are 1870 nm, 1930 nm and 2210 nm.
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. 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 120 nm. The waveguide core is embedded between 2 µm 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 150 µm as well as 90 µm 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 chirped into 1000 x 150 µm$^2$ and 1500 x 90 µm$^2$ single emitters. 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 1 cm long bar were fabricated. 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.

3. SINGLE EMITTER PERFORMANCE

Figures 1 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%. This leads to an output power of 1±0.1 W at 4 A for all different wavelengths. The threshold current density keeps nearly constant between 1870 nm and 1960 nm. For 2210 nm the threshold current density slightly increases.

The measured far field distribution (1/e$^2$ definition) in the slow and in the fast axis is shown in figure 2 for a 150 x 1000 µm$^2$ and a 90 x 1500 µm$^2$ 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 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 standard fibers.

In figure 3 the shifts of the emission wavelength of 1000 150 µm$^2$ single emitters at 1850 nm and 2210 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.
Figure 1. 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>
<thead>
<tr>
<th>emitting wavelength (nm)</th>
<th>1870</th>
<th>1940</th>
<th>1960</th>
<th>2210</th>
</tr>
</thead>
<tbody>
<tr>
<td>emitter width (µm)</td>
<td>150</td>
<td>90</td>
<td>150</td>
<td>150</td>
</tr>
<tr>
<td>resonator length (µm)</td>
<td>1500</td>
<td>1500</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>$J_{th}$ (A/cm$^2$)</td>
<td>170</td>
<td>190</td>
<td>180</td>
<td>220</td>
</tr>
<tr>
<td>s.e. (W/A)</td>
<td>0.32</td>
<td>0.31</td>
<td>0.36</td>
<td>0.30</td>
</tr>
<tr>
<td>$\eta_{max}$ (%)</td>
<td>27.4</td>
<td>26.0</td>
<td>25.3</td>
<td>20.6</td>
</tr>
<tr>
<td>output power @ 4A (W)</td>
<td>0.97</td>
<td>1.00</td>
<td>1.2</td>
<td>0.9</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. Slow axis and fast axis far fields of a 1000 x 150 µm$^2$ and a 1500 x 90 µm$^2$ single emitter at 1930 nm. The measurements have been performed at a heat sink temperature of 20 °C in cw operation.

Figure 3. 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.

4. DIODE LASER ARRAY PERFORMANCE

Linear arrays of 19 broad area emitters with a strip width of 150 µm (30% fill factor) or 90 µm (20% fill factor) 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 for the 30% fill factor bars and 1500 nm for the 20% fill factor bars. Table 2 gives an overview of the electro-optical characteristics of 1940 nm and 2200 nm laser bars and together with fig. 4 a comparison of 20% and 30% fill factor bars at 1940 nm. For an actively cooled 1940 nm laser array with 30% fill factor a maximum output power of 19.5 W at 68 A has been achieved.
A maximum cw power of 16 W has been achieved at 75 A for a 19 emitter array emitting at 2200 nm, 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 30 A for an array emitting at 2200 nm. This is to our knowledge the highest cw output power and wall-plug efficiency of a diode laser array emitting above 2 µm ever reported.

<table>
<thead>
<tr>
<th>emitting wavelength (nm)</th>
<th>1940</th>
<th>1940</th>
<th>2200</th>
</tr>
</thead>
<tbody>
<tr>
<td>number of emitters</td>
<td>19</td>
<td>19</td>
<td>19</td>
</tr>
<tr>
<td>emitter design (µm)</td>
<td>150 x 1000</td>
<td>90 x 1500</td>
<td>150 x 1000</td>
</tr>
<tr>
<td>fill factor</td>
<td>30%</td>
<td>20%</td>
<td>30%</td>
</tr>
<tr>
<td>heat sink</td>
<td>passive</td>
<td>passive</td>
<td>passive</td>
</tr>
<tr>
<td>heat sink temperature (°C)</td>
<td>20</td>
<td>20</td>
<td>17</td>
</tr>
<tr>
<td>( I_{th} ) (A)</td>
<td>5.1</td>
<td>6.0</td>
<td>7.05</td>
</tr>
<tr>
<td>s.e. (W/A)</td>
<td>0.28</td>
<td>0.34</td>
<td>0.30</td>
</tr>
<tr>
<td>( \eta_{max} ) (%)</td>
<td>29</td>
<td>26</td>
<td>23</td>
</tr>
<tr>
<td>operation current @ 10W (A)</td>
<td>41</td>
<td>37</td>
<td>41</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 4. 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 5. CW output power vs. current characteristics recorded for diode laser arrays emitting at 1940 nm and 2200 nm.
5. **Laser Modules**

**Figure 6.** CW output power vs. current characteristics for fiber coupled single emitters emitting at 1930 nm and 2210 nm. All measurements have been performed at 20 °C heat sink temperature.

**Figure 7.** CW output power vs. current characteristics for a fiber coupled laser array emitting at 1940 nm. All measurements have been performed at 20 °C heat sink temperature.
The diode laser single emitters and laser arrays are suitable for fiber coupling. In fig. 6 broad-area single emitters with 150 x 1000 µm² design emitting at 1930 nm and 2210 nm have been coupled into 200 µm core fibers (NA=0.22). At 1930 nm maximum peak power ex fiber was 290 mW corresponding to a coupling efficiency of 75%. At lower output powers coupling efficiency is in the range of 85%. For 2210 nm a maximum peak power ex fiber of 230 mW has been demonstrated, corresponding to a coupling efficiency of 85%.

Fig. 7 shows the results for fiber coupled laser arrays at 1940 nm. For a 1-bar module a maximum peak power ex fiber of 7.4 W has been established for a 400 µm core fiber (70% coupling efficiency). Taking an 800 µm core fiber 8.7 W 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 18 W has been measured out of a 600 µm core fiber with NA 0.22.

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 for applications in medical treatment, materials processing and pumping of solid state lasers.

High power diode lasers at 1870 nm, 1930 nm and 2210 nm with 1 W 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 1940 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 2200 nm 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 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.

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