High-brightness 800nm fiber-coupled laser diodes

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ABSTRACT

Fiber-coupled laser diodes have become essential sources for fiber laser pumping and direct energy applications. Single emitters offer reliable multi-watt output power from a 100 m lateral emission aperture. By their combination and fiber coupling, pump powers up to 100 W can be achieved from a low-NA fiber pigtail. Whilst in the 9xx nm spectral range the single emitter technology is very mature with >10W output per chip, at 800nm the reliable output power from a single emitter is limited to 4 W – 5 W. Consequently, commercially available fiber coupled modules only deliver 5W – 15W at around 800nm, almost an order of magnitude down from the 9xx range pumps.

To bridge this gap, we report our advancement in the brightness and reliability of 800nm single emitters. By optimizing the wafer structure, laser cavity and facet passivation process we have demonstrated QCW device operation up to 19W limited by catastrophic optical damage to the 100 μm aperture. In CW operation, the devices reach 14 W output followed by a reversible thermal rollover and a complete device shutdown at high currents, with the performance fully rebounded after cooling.

We also report the beam properties of our 800nm single emitters and provide a comparative analysis with the 9xx nm single emitter family. Pump modules integrating several of these emitters with a 105 μm / 0.15 NA delivery fiber reach 35W in CW at 808 nm. We discuss the key opto-mechanical parameters that will enable further brightness scaling of multi-emitter pump modules.

Keywords: Single emitter, laser diode, high-power laser, facet mirror reliability, fiber coupled emitter, mirror passivation, facet coating, multi-emitter modules, fiber laser pump.

1. INTRODUCTION

The increasing demand for high-brightness sources has driven the development of a new class of diode laser modules. High-power laser diodes based on single emitter technology are packaged with relatively simple and inexpensive coupling optics to produce several tens of watts of optical output from low-NA delivery fiber. Reliable state-of-the-art single emitters delivering ~10 W out of a ~100 μm lateral aperture in the 9xx nm spectral range, are the most common building blocks of fiber laser pumps [1].

In contrast to the impressive advances in the output power of 9xx nm laser diodes, single emitters at 800 nm range exhibit only rather modest reliable output powers of 5 W – 6 W from a ~100 μm aperture. Based on the experience acquired in the 9xx nm wavelength range, we have developed a new low-loss asymmetric laser structure for diode lasers emitting at 800 nm. The improved epitaxial layer structure combined with an optimized facet passivation process has enabled us to approach 10 W operating power per emitter, with a 35 W ex-fiber CW output for a fully integrated fiber-coupled multi-emitter module with a low NA of 0.15 and a 105 μm fiber core. The results presented in this paper clearly indicate that the performance of 800 nm single emitters can be further improved to achieve a reliable operation at >10 W in the near future. Embedding such a diode in a fiber coupled package will enable fiber laser pumps at 800 nm with a performance and cost comparable to those of the 9xx nm family.

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The paper is organized as follows: in Section 2, we start off by describing our epitaxial and chip design that enabled the power of 800 nm emitters to be upgraded. We also discuss the challenges of increasing the catastrophic optical damage threshold to achieve high reliability performance. In Section 3, the emitter results are presented and their beam divergence compared with devices at other wavelengths. The integration of single emitters into fiber coupled modules and the performance achieved are covered in Section 4. We then conclude with a summary in Section 5.

2. EPITAXY AND EMITTER DESIGN

2.1 Epitaxial design

In order to achieve consistent device performance at 800 nm, we have developed a common Al-based epitaxial platform utilizing an asymmetric structure design [2] based on its proven performance at 9xx nm wavelengths. We made minor changes to the thickness and position of the GaAsP quantum well to achieve wavelength adjustment to 800nm. By using an asymmetric waveguide structure as shown in Figure 1, the optical mode can be shifted into the lower waveguide cladding, leading to a reduced overlap of the mode (shaded area on Figure 1) with the highly absorbing p-doped layers. Through a detailed simulation of the laser structure, we were able to optimize the optical mode overlap with the charge carrier profiles without a significant forward bias penalty. We achieved a very low optical loss of 0.5 cm⁻¹ enabling laser wall-plug efficiencies (WPE) in excess of 60% to be achieved. The large mode waist also results in a reduced power density on the output facet, which increases the laser's COMD level.

2.2 Laser chip design

We defined the lateral emitting aperture at ~90µm for compatibility with 105 µm / 0.15 NA fiber coupling. Wafers were processed into single emitters with 4 mm and 5 mm cavities to investigate the trade-off between the efficiency and power. The extended cavity length ensured high thermal and electrical conductivities of the devices by increasing their active area. The lasers also incorporated a current block region at either facet, where current injection was suppressed with a view to minimizing the joule heating in the facet areas. After wafer fabrication, the facets of the devices were passivated and coated with 2% / 97% AR / HR coatings, and the chips singulated and soldered on ceramic heat-spreaders. The resulting Chip-On-Carrier (COC) parts were assembled onto CS mounts for characterization in CW regime. The photograph of Figure 2(a) shows a fully assembled and wirebonded COC, with the lateral emission profile shown in Figure 2(b).
2.3 COMD and facet passivation

Laser diode reliability is strongly correlated to the $p$-$n$ junction temperature. Thermal effects are particularly critical in the facet region of the laser cavity, where heating causes the energy band gap to shrink leading to yet more absorption and heating. We have developed [3] a steady-state thermal laser model to enable us to investigate the heat distribution in the device and engineer the facet region for minimum thermal load. Catastrophic Optical Mirror Damage (COMD) is well known to be a main failure mechanism limiting the single emitter performance in high current/high power operation.

Under nominal operating conditions, the 808 nm single emitters produced 9 W optical output at a 9 A drive current, with the facet estimated to be $\Delta T = 35$K hotter than the heat-sink. We also modeled the effect of a dark defect (a local absorber placed on or next to the facet), which lead to a much more significant localized heating with $\Delta T = 190$K. Such defects are likely to trigger thermal runaway processes leading to facet meltdown in the waveguide layer such as photographed in Figure 3. In Figure 4, the high resolution SEM image was taken using focused ion beam analysis allowing the COMD site to be profiled.

![Figure 4. High-resolution SEM profile of the COMD spot as observed from a FIB pit. The red line illustrates the optical intensity distribution simulated for the specific wafer structure design. Facet heating was probably started by a dark defect absorber (which could form a thermal source of up to ~ 300 mW according to our model) and escalated into an extended COMD line feature across the emitter width as seen in Figure 3.](image)
We also found that the effect of dark-defect heat sources was almost impossible to mitigate by modifying the chip design or packaging parameters such as metallization thickness or facet position versus the heat-sink. The modeling results underscore the importance of an appropriate choice of dielectric films for facet passivation and coating that should provide a minimum absorption at the lasing wavelength.

In our earlier study [3], we reported the demonstration of a reliable facet passivation technology which was particularly efficient in the 9xx spectral band. In Table 1 below, one can see a clear trend of increasing difficulty in obtaining high-power laser operation from 980 nm down to 808 nm. At 980 nm, one can employ dielectric facet passivation with excellent results. However, this technique was found inadequate at shorter wavelengths, where an adjustment of the process parameters to the material structure of a specific wafer design was required. Our progress against the baseline of Ref.[3] can be seen on the second line of Table 1, where our 808 nm benchmarks have been significantly improved.

Table 1. Summary of the maximum QCW powers achieved across the 800-9xx nm range using dielectric passivation layer technologies.

<table>
<thead>
<tr>
<th>Passivation</th>
<th>980nm</th>
<th>940/925nm</th>
<th>915nm</th>
<th>808nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011 status in</td>
<td>19W</td>
<td>13W</td>
<td>12W</td>
<td>9W</td>
</tr>
<tr>
<td>Ref.[3]</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In this paper</td>
<td>19W</td>
<td>17W</td>
<td>16W</td>
<td>14W</td>
</tr>
</tbody>
</table>

In order to avoid thermal rollover, we use quasi-CW 200 µs pulses on a low duty cycle for the characterization of the COMD level following each dielectric passivation process run. Figure 5 shows a typical L-I curve with COMD for an 800 nm single emitter.

![Figure 5. Quasi-CW L-I curve for an 800nm single emitter measured with a 200 µsec pulse width and low duty cycle of 0.5%. A COMD-limited peak power of 19 W at 20 A is achieved.](image)

In order to benchmark the performance of our facet passivation process across several wavelengths, we calculated the COMD power density by normalizing the measured peak power to the emitting area for each epitaxial design across 800 nm – 1085 nm. The emitting area is defined as the product of the lateral aperture and the 1/e² width of the near-field vertical spot modeled for a specific wafer design at each wavelength. As can be seen from the chart of Figure 6, our passivation technology delivers a COMD power density of 20 MW/cm² for all of our working wavelengths, including 800 nm.

The nearly constant COMD power density independent of wavelength is achieved by careful wafer structure engineering and optimization of the process parameters for our passivation technology. Work is underway to further improve the COMD and reliability benchmarks of our single emitters.
3. SINGLE EMITTER PERFORMANCE

3.1 Laser chip electro-optical performance

The light-current (L-I) characteristics and WPE of 808 nm COC assembled on CS mounts in CW operation at $T = 25^\circ$C are plotted in Figure 7(a). The slope efficiency is 1.1 W/A with a peak WPE of 54% at 6 A. 14 W power is reached at 17 A for devices with facet passivation, and only 9 W at 9 A for devices without any facet treatment prior to the AR / HR coating. A narrow spectral linewidth of 1.6 nm FWHM is observed at a drive current of 9 A, see Figure 7(b).

3.2 Laser beam slow axis divergence

In spite of the progress with increasing the CW power of 800nm single emitters, the slow axis beam divergence remains an open issue. Indeed, both the absolute divergence angles and their variation from chip to chip carry a significant yield penalty as illustrated in Figure 8, where the chip statistics with given divergence at $\lambda = 808$ nm (a) is juxtaposed with that at 9xx nm (b). In these histograms, the chips are binned by slow axis divergence defined as the $1/e^2$ angle. The
angular values of most 808 nm chips lie in the range of 14° - 20° in contrast with the much lower – and narrower – distribution for 9xx nm devices, which are confined within a range of 9° - 15°. The large slow axis divergence and its high variability at 808 nm adversely affect the fiber coupling efficiency of these devices.

Figure 8. Histograms of chips-on-carrier (COC) binned by slow axis divergence at 808nm (a) and 9xx nm (b).

Another issue with the beam quality at 808 nm is its dependence on the drive current. Figure 9 shows the broadening of the beam divergence when measured in QCW at 13 A relative to 7 A current.

Figure 9. Slow axis far field profiles of 808 nm emitters measured at 7A and 13 A in QCW.

4. MULTI-EMITTER MODULES

At SCD, we are completing the development of the NEON family of multi-emitter fiber-coupled modules, with product versions at several wavelengths across 800 nm – 1085 nm. While these share a common opto-mechanical architecture, the optical elements and alignment process are adjusted to specific beam parameters at each operating wavelength.

As described in Sec.2.2, the fabricated chips are facet passivated and coated followed by their assembly onto COC, which serves as a piece part for subsequent module integration. After testing and screening to specific pass/fail criteria (depending on product requirements), the COCs are integrated in NEON multi-emitter packages with a common multimode output fiber.

The optical assembly process involves careful alignment of each individual single emitter/laser beam, with some steps requiring sub-micron / milliradian positioning tolerances. The large slow axis divergence of 800 nm emitters presents a serious coupling issue, since it exceeds the angular acceptance limits of the module’s optical design. As a result, our NEON product prototypes at 808 nm exhibit a lower fiber coupling efficiency as compared to the 9xx nm modules at the current stage of development.

We have developed an inline imaging technique for beam control and positioning both in the angular (collimated far-field profile) and spatial (image formed on the fiber entrance) spaces. The images of Figure 10 (a) show the far-fields of the collimated beams inside the module relative to the angular acceptance cone of a 0.15 NA fiber. As can be seen, the
leftmost and rightmost beams overfill the fiber NA of 0.15 causing both a drop in the coupling efficiency and heating of the polymer fiber coating / jacket due to the “mode-stripping” of the light propagating in the fiber clad. Figure 10 (b) shows the far field of the ex-fiber emission from the output pigtail end, with most of the power contained within the 0.17 NA cone marked by the red circle, with the outlying angular power content likely to cause fiber splice heating downstream. Note that the calculated power content values are estimates that are highly sensitive to the electronic background subtraction performed by the camera and subsequent image processing.

To summarize, the fiber NA overfill issues due to the excessive far-field divergence of 808 nm emitters pose a significant engineering problem that must be solved to reach the ~80% fiber coupling efficiency benchmarks achieved in multi-emitter modules in the 9xx – 1100 nm spectral band.

4.1 Multi-emitter module performance at 800 nm

Figure 11(a) shows the light-current (L-I) characteristic of a typical 800 nm NEON module in CW operation at $T = 25^\circ$C. 35W ex-fiber power with a 35% wall-plug efficiency is obtained at 9 A. In Figure 11(b), the emission spectrum under the same conditions is shown with a linewidth < 3.5 nm FWHM.

4.2 Multi-emitter module performance at 915, 940, and 975 nm

Single emitters at 9xx nm deliver much higher brightness than the 800 nm devices reported here. The former achieve reliable high-current CW operation at 12 A compared to 9 A for 800 nm devices, and with a lower slow axis divergence at that. We have developed common design rules for single emitters in the 9xx band with only minor changes in the wafer layer structure to adjust for specific wavelength requirements at 915, 940, 950 or 975 nm. We also apply a very similar optical design and alignment process for the assembly of NEON multi-emitter fiber packages across all wavelengths. Figure 12 shows a collection of typical L-I and wall-plug efficiency curves (ex-fiber, CW) for NEON prototype modules at three popular wavelengths of 915, 950 and 975 nm, with all 3 NEON versions exhibiting very
similar performance: >50 W ex-fiber CW output at 12 A with a WPE above 40%. The spectral linewidth is typically 4 nm – 6 nm FWHM. These modules are currently at prototype level and their development is nearing completion.

Figure 12. Performance of NEON multi-emitter package prototypes at 915, 950 and 975 nm (ex-fiber, CW mode).

5. SUMMARY

We have presented our progress in the development of high-brightness single emitters at 800 nm. We demonstrated a peak power of 14 W at 17 A in CW operation, and 19 W QCW power with a peak efficiency > 54%. The performance improvement was enabled by the optimization of the wafer structure design and adjustment of the facet passivation process.

We report the issue with a high far-field divergence of the slow axis emission at 800 nm and compare it with that of single emitters in the 9xx nm band. We attribute the higher performance of the 9xx nm devices to the nominally lower aluminum content in the wafer layer structure, including the quantum well and active layer. We therefore believe that further performance improvement with a decreased beam divergence is feasible.

By integrating single emitters into multi-emitter NEON modules, a CW output of 35 W is obtained from 105 µm / 0.15 NA fiber at 9 A in 800 nm modules, and 50 W at 12 A in 9xx nm modules.

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