Power degradation and reliability study of high power laser bars at quasi-CW operation

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\textbf{ABSTRACT}

The solid state laser relies on the laser diode (LD) pumping array. Typically for high peak power quasi-CW (QCW) operation, both energy output per pulse and long term reliability are critical. With the improved bonding technique, specially Indium-free bonded diode laser bars, most of the device failures were caused by failure within laser diode itself (wearout failure), which are induced from dark line defect (DLD), bulk failure, point defect generation, facet mirror damage and etc. Measuring the reliability of LD under QCW condition will take a rather long time. Alternatively, an accelerating model could be a quicker way to estimate the LD life time under QCW operation.

In this report, diode laser bars were mounted on micro channel cooler (MCC) and operated under QCW condition with different current densities and junction temperature ($T_j$). The junction temperature is varied by modulating pulse width and repetition frequency. The major concern here is the power degradation due to the facet failure. Reliability models of QCW and its corresponding failures are studied.

In conclusion, QCW accelerated life-time model is discussed, with a few variable parameters. The model is compared with CW model to find their relationship.

\textbf{Keywords:} high power semiconductor laser, reliability, failure analysis, quasi-CW

1. INTRODUCTION

With the development of high power semiconductor lasers (HPL), the peak power is significantly increased and the application fields of HPL were gradually expanded. 808nm and 940nm diode laser can reach QCW 600W and 800W, respectively (reference needed), with industry level reliability.\textsuperscript{1} Their most iconic applications are solid state laser (SSL) pumping sources. As SSL pumping sources, the operation condition has a feature of very high peak power but low average power (low duty cycle). Pulse width less than 400s and frequency less than 1000Hz is a typical QCW operation condition, which produces a duty cycle no more than 10%.

A life time of at least 1 billion shots are required for industry level application. In general, end of life (EOT) is defined as the output power dropping below 80% of initial power or operated current increasing above 120% of initial current. In addition, as SSL pumping sources, the stability of central wavelength of pumping source is very critical to maintain the efficiency of the entire pumping system. This is different from most of laser applications, such as direct use in industry applications, biomedical and illumination, where only power is concerned.

Currently, the reliability of laser working at CW mode had been well studied, reliable methods and tools were established to evaluating the reliability and MTTF. Aging testing of HPL at QCW condition changes the reliability modeling and failure mode, due to the involved thermal fatigue. Apart from junction temperature and facet power density, pulse width and frequency are two additional variables need to be taken into account. It is worthwhile to mention that, at the same average power, the combinations of pulse width and frequency could dramatically affect the lifetime of HPL. The well-established reliability mode may not be the most suitable tool for HPL device. However, very few results are published regarding the reliability of high power laser under QCW operation.\textsuperscript{2}

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2. EXPERIMENTAL WORK

2.1 Device structure and performance

A semiconductor laser was P-side-down mounted on a micro-channel cooler (MCC), as shown in Fig.1. Indium-free bonding technique was applied. AuSn solder, so-called hard solder, was used instead of Indium to bond the bar to submount. AuSn alloy has a much higher melting point. AuSn solder is more reliable at high temperature and also more robust to temperature and stress cycling. A CuW submount was placed between laser bar and cooler, which had a very close coefficient of thermal expansion (CTE) to GaAs substrate and adds extra strength to the laser bar. A CuW submount was placed between laser bar and cooler, as a buffer layer to overcome the CTE mismatch between GaAs-based laser bar and MCC made of oxygen-free Cu. The negative electrode was connected to the substrate side of the laser bar by gold wire bonding. Standard commercial QCW 1-cm wide 808nm 300W diode laser bars from a state-of-art supplier were chosen, which have a filling factor of 75%, 150m pitch, 100m emitter width and a cavity length of 1.5mm. These diode laser bars have no facet passivation. The thermal resistance of above Indium-free bonded laser device is 0.4k/W, determined under a condition of CW 100W, water flux of 0.15L/min at room temperature.

Figure 1. Structure and performance of hard soldered micro channel cooler 1cm wide diode laser bar device. Typical operation condition is 300W, 200us 400Hz at 25°C.

Fig.1 shows a typical LIV curve and spectrum at 25°C (coolant temperature) under a very common QCW 300W (200s at 400Hz) operation with a wafer flow of 0.15L/minute as a SSL pump source. At this condition, the combination of junction temperature and power could not drive the device to end of life in a reasonable time. Previous result showed devices with a similar structure has >2% power drop after 2000 hours operation. To determine the laser reliability performances under different stress conditions, a few life test conditions were used as listed in Tab.1, to accelerated the aging process. The variable parameters were pulse width, frequency and power. All tests were done at 25°C and the junction temperature was changed by the combination of above parameters. Condition No. 2, No. 4 and No. 5 would shorten the life test to reasonable range such that an obvious power drop could be found after 1000 hour life test. However the exactly accelerating factor is not clear yet.

2.2 Life test

Before starting life test, all devices had their performance recorded, including L-I curves, spectra and near field images. Because of the water cooling system limitation, all life tests were operating with water coolant at a temperature of 22+/−2°C, instead of 25°C. A group of 10 devices operated at condition No. 5 as listed in Tab. 1. Regarding the power monitoring, the devices in life test group 1 were dismounted from life test chamber and had their power measured at 270A on a separated test bench each week. The end of life was determined
Table 1. 5 different test conditions of parameter combinations and their corresponding performance. Three marked conditions are used in later life tests.

<table>
<thead>
<tr>
<th>No.</th>
<th>Power</th>
<th>Current</th>
<th>Pulse width &amp; Frequency</th>
<th>Tj (degC)</th>
<th>Life test</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>300</td>
<td>245</td>
<td>200s 400Hz</td>
<td>35.6</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>320</td>
<td>270</td>
<td>200s 1000Hz</td>
<td>48.2</td>
<td>Group 2</td>
</tr>
<tr>
<td>3</td>
<td>300</td>
<td>300</td>
<td>300s 600Hz</td>
<td>51.4</td>
<td>-</td>
</tr>
<tr>
<td>4</td>
<td>350</td>
<td>300</td>
<td>400s 500Hz</td>
<td>54.1</td>
<td>Group 3</td>
</tr>
<tr>
<td>5</td>
<td>425</td>
<td>380</td>
<td>500s 400Hz</td>
<td>69.2</td>
<td>Group 1</td>
</tr>
</tbody>
</table>

if the power dropped below 80% of the initial value at 0 hours. Two groups of devices, 6 and 10 pieces, were operating at condition No. 2 and condition No. 4, in an in-situ monitored life test system. Their power and wavelength were in-suit monitored and recorded every 30 minutes. A single integrating sphere with power detector and spectrometer moved along an array of operating devices horizontally. The in-situ life test system had better accuracy and reproducibility than the system without in-situ monitoring because the heat sink and the characterization tool are not changed during the life test. Measuring power and spectrum simultaneously also greatly helped the failure mode analysis and generated much more valuable data because the real time information.

3. RESULTS

3.1 Life test results

10 devices were operated under condition 380A, 500s at 400Hz, as shown in Tab.1 (life test group 1). This condition had the highest stress and resulted a shortest life time. 3 devices and 7 devices showed significant power drop during power measurement at 114 hours and 286 hours. Unfortunately, the failed time could only be estimated by tracking temperature change of life test chamber, which was not sensitive or accurate enough. After visual inspection under optical microscopy, continuous areas of fact damages were found from all 10 devices. An example of visual inspection of device SN1950 (device #1) is shown in Fig.3. Because gold metal are lift-off inside the groove and AuSn solder cannot attached to exposed insulator layer, three dark areas at the middle and sides are created. These voids are found before life test and do not affect the heat dissipation. In Fig.2, a COMD spot was cycled. COMD was confirmed by comparing near field image at 45A before and after life test, in Fig.3. The damaged emitters were location in one side of bar in a group, rather than randomly located. It may be related to the non-uniform thermal resistance across different emitters. At the very high line power density condition, varies of defects could result this issue, such as voids at bonding interfaces, AuSn solder composition variation, or stress from CTE mismatch between bar, submount and MCC heatsink.

![Figure 2](image2.jpg)

Figure 2. The optical microscope image of SN1950 was captured at the location where the continuous COMD starts.

Ultrasound scanning microscope is one of the most suitable analytical method here. Fig.4 show no void at the bonding interface. Some emitters of device SN2148 have solder shortage at the front facet, which could create locate temperature increasing at near the facet area and induces mirror damage. However, the position of solder shortage and COMD cannot perfectly match.
Figure 3. Near field image of device SN1950 (top), SN2148 (mid) and SN2138 (bottom) before and after life test. The optical microscope image of SN1950 was captured at the location where the continuous COMD starts.

Figure 4. Ultrasonic scanning microscopy images of SN1950 (top) and SN2148 (bottom). The images show no voids at the bonding interface.

Both power and wavelength of LT group 2 were in-situ monitored. The peak operating current was 270A, with a pulse width of 200us and a repetition rate of 1000Hz, which produces an operating optical power of 320W. Two devices (device #9 and device #10) failed at 260 hours; one device (device #1) showed power degradation and reached EOT at 550 hours, as shown in Fig. 5. The power of the remaining 7 devices remained stable till 650 hours. All devices in group 2 were dismounted at 260 hours for system maintains, which led to a performance change of devices, power drop and wavelength increase at the same point of time. The two devices failed at the same time after the power dropping could be a sudden failure induced by unstable system. Between 320 hours and 340 hours, a power increase was detected. Since the real time monitored wavelength remained stable, we believed that it is a power meter issue, instead of device performance change.

A few interesting phenomena were found from the life test result of device #1. All power drops had clear steps and developed in the later stage of life test. The failed emitters should increase the current density of the lasing lasers because the voltage of the failed laser was not clamped as the lasing lasers, which should further accelerate the aging process of the lasing lasers besides the additional heat generated by the neighboring failed lasers. Till 650 hours, the remaining 7 devices finished 2.3 billion shots without any noticeable power drop.

The failed device #1 was further investigated. A near field image captured at 40A under CW operation, and an near field image were recorded at 520 hours. As shown in the top image of Fig.6, part of the failed emitters still had weak intensity but a split pattern. The bottom image of Fig.6 shows the real time central wavelength increases at the same time when the power drops. The increase lasing wavelength is due to the junction temperature increase resulting from the increase current density of the lasing lasers and the additional
Figure 5. Till 650 hours, 3 of 10 devices failed. Two devices showed sudden failure at 260 hours at early stage of test and one device showed power degradation and reach EOT at 550 hours. The rest of 7 devices were stable.

heat generated from the failed lasers. The near field images of device 9 and device 10 which are not presented because very few emitters survived. Only 2 data points (1 hour) were in-situ collected during the data drops.

Figure 6. (top) Near field image of device #1, captured at 40A CW. (bottom) Power and central wavelength data simultaneously monitored.

In parallel, 6 devices were tested at 300A, as shown in Tab.1 and monitored using the same in-situ instruments. The pulse width was double to 400us while the repetition rate is half to maintain a same duty cycle of 20%, in order to increase the junction temperature by 6.1°C with respect to that of Group 2. All 6 devices showed a slow power degradation of 6.7%-13.9% after 240 hours, as shown in Fig. 7.

3.2 Failure analysis

The failed device analysis does not show failure related to die bonding at the soldering interface. Indium-free hard solder bonding technique completely eliminates the solder void and squeezing out caused by temperature cycling under QCW operation, which is one of major limitation of Indium soldered devices. In above experiments, the most common failure mechanism is mirror damage, or so-called, catastrophic optical mirror damage (COMD).
The COMD has a few features, 1) COMD generated at random location of the bar; 2) COMD starts from a single emitter, then develop into a group of continuous COMD; 3) devices without mirror damage have very stable power performance for a very long time, in order of billions shorts.

It is known that COMD threshold is lower in high bandgap material. The COMD threshold is measured by probing each emitter on a home-made bare bar test system. 2 pieces of 75%FF bars from two different wafers and 2 piece of 50FF% bar from one wafer are tested, in order to reduce the possible the measurement error. In total, 6 bars from the same supplier with similar facet coating technique are tested. After converting the results into line power density, they should have similar value.

The test system generates a current of 5s pulse width and 100Hz repetition rate, at 25°C. The current increases at a chosen step, till a large enough value to generate COMD as indicated by the power meter showing a significant drop. Results from 4 75%FF bars are presented in Fig.8. The average COMD power is $8.1 \pm 0.56$W, with a maximum of 9.2W and minimum of 5.9W. A average line power density is 81mW/m without face passivation. Applying the identical measurement method to 50%FF bars, the resulted line power density of 77mW/um is very similar, as shown in Fig.9.

Influence from high junction temperature to COMD threshold is studied by dividing emitters on a single 50%FF bar into four groups and testing them at a heat sink temperature of 25°C, 45°C, 65°C and 75°C, respectively. The resulted COMD show no difference from 25degC to 75degC, as shown in Fig.9.
4. LIFETIME MODEL AND RELIABILITY STUDY

Reliability data of CW 100W (110A) diode laser bars with different filling factor but the same vertical epitaxial structure were provided from suppliers. The geometry difference was converted into a line power density (LPD=20mW/um) difference and the structure difference of device were converted into junction temperature ($T_j=40.2\text{degC}$). The data showed the lifetime of 8 devices. When the test stopped at 4650 hours, 5 of 8 devices failed with details as shown in Tab.2. The data were analyzed by Weibull failure distribution, as shown in 1, where $\beta$ is the shape parameter and $\eta$ is the scale parameter. Fig.10, a unreliability function of time $F(t)$ is generated.

$$F(t) = 1 - \exp\left(-\frac{t}{\eta}\right)^{\beta}$$ (1)

Table 2. Reliability data provided from supplier. 5 of 8 device failed during a long of 4650 hours.

<table>
<thead>
<tr>
<th>No.</th>
<th>Failed Time (hours)</th>
<th>Unreliability</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3000</td>
<td>8.3%</td>
<td>failed</td>
</tr>
<tr>
<td>2</td>
<td>3380</td>
<td>20.2%</td>
<td>failed</td>
</tr>
<tr>
<td>3</td>
<td>3580</td>
<td>32.1%</td>
<td>failed</td>
</tr>
<tr>
<td>4</td>
<td>4000</td>
<td>44.0%</td>
<td>failed</td>
</tr>
<tr>
<td>5</td>
<td>4530</td>
<td>56.0%</td>
<td>failed</td>
</tr>
<tr>
<td>6</td>
<td>4650</td>
<td>-</td>
<td>drop to 90%</td>
</tr>
<tr>
<td>7</td>
<td>4650</td>
<td>-</td>
<td>drop to 92%</td>
</tr>
<tr>
<td>8</td>
<td>4650</td>
<td>-</td>
<td>drop to 98%</td>
</tr>
</tbody>
</table>

To extend this data further to QCW operation, the junction temperature $T_j$ and LPD $P$ of QCW operation condition 2, 4 and 5 in Tab.1 were calculated, to estimate the accelerating factor by Eqa.2. To use CW life time data as reference, $\eta_0=4650$ hours, $T_0=40.2\text{degC}$ and $P_0=20mW/um$. To link the QCW and CW life time, a few assumptions are made. A typical thermal active energy $E_A=0.45eV$ and exponent of power acceleration $n=5$ are chosen here. In addition, life time will only reduce when laser is activated (on-time).

$$\eta(T_j, P) = \eta_0 \exp\left(\frac{E_A}{k_B\left(\frac{1}{T_j} - \frac{1}{T_0}\right)}\right)(\frac{P}{P_0})^{-n}$$ (2)

The results are presented in Tab. 3. The resulted EOT (hours) is the real test time and has involved the duty cycle parameter. The experimental results is at least 1 or 2 order shorter than estimated life time. But the estimated result at condition 4 (400us, 500Hz, 350W) has the longest life time, following by Condition 2 (200us, 1000Hz, 320W) and condition 5 (500us, 400Hz, 425W), in sequence, which agrees with experiment result. As mentioned in failure analysis section, almost all power drop are caused by mirror damage. The failure
mechanism is very different from CW operation, where power degradation is caused by defect propagation, but facet reliability is not the major limitation.

Table 3. Estimated life time of different QCW operation conditions, based on provided CW reliability data.

<table>
<thead>
<tr>
<th>No.</th>
<th>LPD (mW/um)</th>
<th>Pulse Width (us)</th>
<th>Frequency (Hz)</th>
<th>Tj (degC)</th>
<th>Acce. factor</th>
<th>EOT (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CW</td>
<td>20.0</td>
<td>-</td>
<td>-</td>
<td>40.2</td>
<td>1</td>
<td>4650</td>
</tr>
<tr>
<td>2</td>
<td>51.6</td>
<td>200</td>
<td>1000</td>
<td>48.2</td>
<td>174.8</td>
<td>26.6</td>
</tr>
<tr>
<td>4</td>
<td>55.9</td>
<td>400</td>
<td>500</td>
<td>54.3</td>
<td>70.4</td>
<td>66.1</td>
</tr>
<tr>
<td>5</td>
<td>68.5</td>
<td>500</td>
<td>400</td>
<td>69.2</td>
<td>392.1</td>
<td>11.9</td>
</tr>
</tbody>
</table>

5. CONCLUSION

Three groups of hard soldered micro channel cooler laser bars were operated at varies of QCW conditions for life test. Three groups had the same duty cycles of 20%, but different combination of pulse width, repetition rate, and current, which resulted in different junction temperatures and LPDs at the facet. As result, different life time are expected. But life test data are very limited and cannot generate statistical significant conclusion due to both ratio of failures and number of failed devices are rather low. Moreover the life tests are still running.

A life time data of laser bars with different geometry designs but the same vertical laser structure is studied. The reliability models of CW and QCW operation are connected by a few assumptions. Based on CW data, the QCW reliability is estimated and the outcome is in the two order of magnitude smaller than experimental result. After failure analyzing, only facet damage was observed. The “power vs. time” plot has obvious steps, which does not match the typical power behavior of slow degradation (wearout failure). This could be the reason why CW reliability model may not be the best choice to predict the reliability behavior at QCW condition. To make the QCW reliability model more effective, the accelerating from line power density could contribute more, vis-a-vis, the contribution from junction temperature should be reduced. More investigation are needed in this area.

In contrast to previous Indium mounted QCW devices, the void free AuSn bonding technique significantly improved the reliability of high power diode laser under QCW operation condition. The life time was tested at a high duty cycle and high junction temperature, to at least 2.3 billion shots. The failure caused by thermal fatigue and current induced electro migration of solder material were not found in all hard soldering device. With the technology development of semiconductor laser, specially improving the defect density of substrate and facet passivation, finding the reliability limitation of high power laser device at QCW condition is an increasing
challenge. An effective method or model to help estimating reliability of QCW operation is desired. This is a
direction of future work after collecting more data.

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