Reliability of High Performance 9xx-nm Single Emitter Diode Lasers

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ABSTRACT

This paper presents reliable high power and high brightness 9xx-nm single emitter laser diodes, which have been designed for various multi-emitter fiber-coupled modules. Diode lasers from legend generation have been life-tested with currents up to 14A at heat-sink and junction temperatures of 50 ℃ and 80 ℃ respectively, and have accumulated more than 15,000 hours of life-test duration. In order to further improve reliable operational power and optimize beam quality, new generation devices have been developed. The new devices demonstrated more than 20W CW rollover power without catastrophic optical mirror damage (COMD). Near-field/far-field patterns have also been improved significantly. In addition to step-stress life-tests, a 7-level multi-cell life-test was designed to investigate acceleration factors relative to the operation conditions. Junction temperatures ranging from 60°C to 110°C and current from 14A to 18A were used in this multi-cell life-test. The ongoing multi-cell life-test has accumulated 1.3 million raw device hours and shown very few device failures in up to 7000 hours duration. Such a low failure rate doesn't allow a meaningful estimation of acceleration factors. When nominal acceleration factors are used, multi-cell life-test data supports ~500 FIT, with 90% confidence, at 10W, 33°C/50°C heat-sink/junction temperatures.

Key words: Reliability, lifetime, life-test, high power lasers, semiconductor laser diodes, multi-cell life-test, failure mode, 980-nm, 915-nm

1. INTRODUCTION

High power broad area (BA) semiconductor lasers at 900-1000nm have been widely employed in many industrial applications. They have been directly used for materials processing and they have been used for fiber laser pumping. For such applications, the broad area diode lasers are coupled into fibers, forming a module to deliver hundreds or thousands of watts of optical power. Such applications require the diode lasers to have high power and brightness. Furthermore, such industrial applications usually require devices to operate at telecom level reliability, with the cumulative device failure rate for two-year operation being less than 2% for modules or FIT score below 2000 for devices. In the last 10 years, the operation power and brightness of multi-mode diode lasers have been improved by a factor of 5 roughly, through techniques such as improved epitaxial design, increased cavity length, better facet passivation technology and improved heat-sinks [1-5]. The reliability of the devices has also been improved. However, reliability data reported so far are still extremely limited. Accelerated life-test has been almost always used, as extremely large number of devices and very long life-test duration are needed to statistically estimate the device's reliability under standard operating conditions. To verify device failure rate and acceleration factors at different stages of laser life, a well-designed multi-cell life-test with multiple acceleration levels must be conducted. So far, only limited numbers of papers have [5-9] reported multi-cell life-test and few papers have been able to report acceleration factors. Even so, in those limited reports, the uncertainties on estimated acceleration factors were not mentioned usually. In most of literature, failure rates or lifetimes at use conditions were simply estimated though nominal parameter values.

In this work, new generation high power 9xxnm multi-mode devices with improved brightness have been developed. Reliability has been extensively studied under accelerated life-test conditions. In particular, a multi-cell life-test, with

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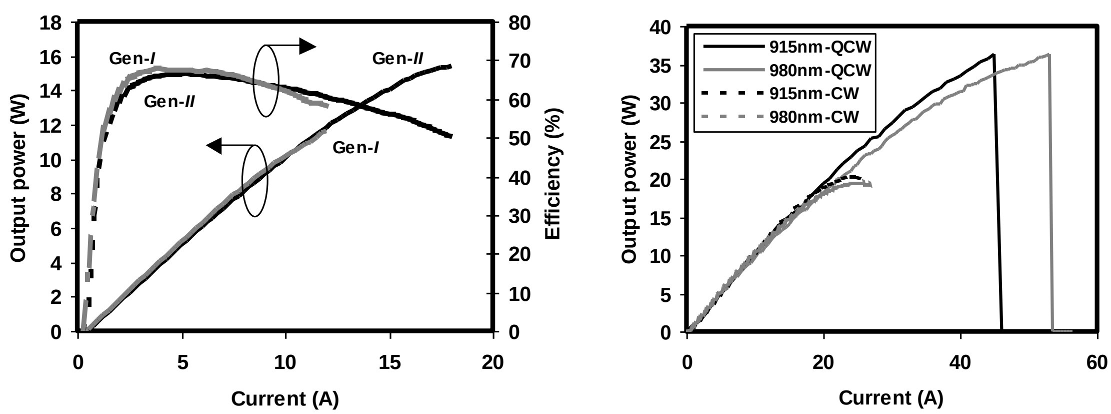
more tha n 200 devices distributed in seven acceleration levels, has been ongoing. 7000 hours have been accumulated up to this time. Results obtained so far will be reviewed and analyzed. The challenges faced in obtaining acceleration factors with reasonable confidence will be discussed. Failure analysis using various techniques and failure modes will also be addressed.

2. HIGH PERFORMANCE 915-980-NM SINGLE EMITTER LASER DIODES

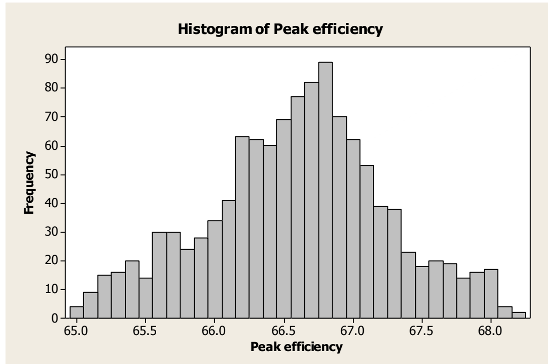
High performance 915/980-nm multi-mode diode lasers were developed as pumping sources in fiber coupled modules with 100um or 200um fiber core sizes [1-2]. Cavity lengths, 3.8 mm or 3.0 mm longer, were used. The vertical laser structure was designed in such a way so that modeled equivalent spot size (d/Γ) is ~1.0 µm, to reduce the power density load on the facets. The layer composition and doping concentration in each layer were optimized for lower voltage, lower loss and better temperature performance. The modeled internal loss is <0.5 cm^{-1}.

The laser structure is grown by Metal-Organic Chemical Vapor Deposition. 95 µm-wide single emitter diode laser chips were fabricated with Six-Sigma process control through multiple lithography steps. The cleaved chips were passivated with proprietary *n*XLT technology and coated with low/high reflectivities on front/rear facets. After coating, single emitter chips were cleaved and bonded p-side down with AuSn solder on AlN submounts. Then these submount were bonded on Cu carriers with Indium solder.

Gen-*I* device used 3.0mm long cavity length. The Gen-*I* 980nm laser diodes' directly measured peak wall-plug efficiency, without any package resistance adjustment, was ~68%. In order to further improve operational power and optimize beam quality, Gen-*II* devices, with 3.8 mm cavity length, were then developed. Continuous wave (CW) optical power and wall-plug efficiency are shown in Figure 1(a). With optimized reflectivities on facets, Gen-*II* devices demonstrated peak efficiency near 67%. The histogram of 1200 980nm devices is shown in figure 1(c). Under CW conditions Gen-*II* diode lasers are tested to ~30A, with a heat-sink temperature of 10°C, as shown in Figure 1(b). When the operating current is close to 30A, both 915nm and 980nm diode lasers show thermal rollover but no COD or COMD failures have resulted. Under Quasi-Continuous Wave (QCW) operation (3 µs pulse width, 1000Hz frequency), these Gen-*II* diode lasers have been tested up to 50A. Catastrophic failures are observed under QCW high current test. The 915nm device fails at ~ 45A and 980nm device fails at ~55A, but at about the same power. Failure analysis on these QCW test failures show that laser diodes have experienced Bulk-defect initiated COD (BCOD) but not facet COMD. Interestingly, this BCOD failure mode seem to be power driven instead of current driven, as 915nm and 980nm laser diodes experience BCOD at different test currents but at about same power level ~35W.



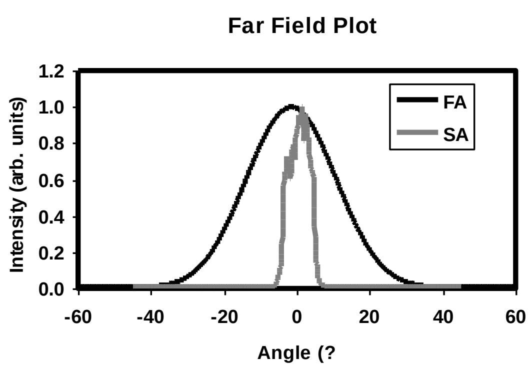
(a) (b)



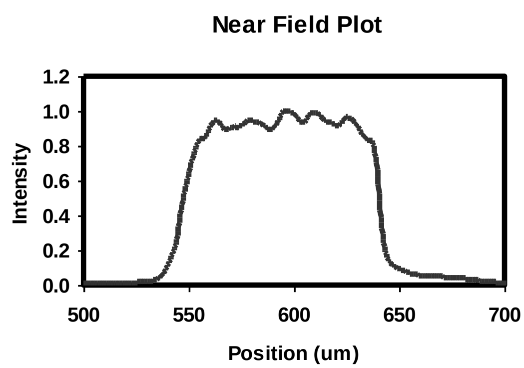
(c)

Figure 1: (a) Optical power and wall-pulg efficiency vs operating current, directly measured under CW condition with heat-sink temperature set at 25°C, for both Gen-*I* and Gen-*II* diode lasers. (b) Optical power of Gen-*II* long 915nm and 980nm diode laser vs operation current, directly measured under CW condition and QCW condition, with test station temperature set at 10°C. (c) Histogram of peak wall plug efficiencies of 1200 980nm devices

With improved design and process control, near field (NF) and far field (FF) profiles of the laser diode were improved. Operating at 10A, EPI layer design reduced the fast axis FF FWHM to around 28° and FW1/e^{2}W to around 48°. The slow axis far field FWHM is ~ 8.5° and FW1/e^{2}W is around 10°, at 10A operation current. Typical slow axis (SA) and fast axis (FA) FF plots at 10A drive current are shown in Figure 2 (a). The lateral NF at 10A operation is shown in Figure 2 (b) with FW1/e^{2}W being ~98um. The lateral NF FWHM width is observed to vary slightly with increasing current. On the other hand, the slow axis FF FW1/e^{2}W width increases relatively quickly with drive current, as shown in Figure 2 (c). Nevertheless, slow axis FW1/e^{2}W is only near 10° at 10A. It is believed that increasing cavity length can further improve the FF, resulting in higher brightness at higher power.



(a)



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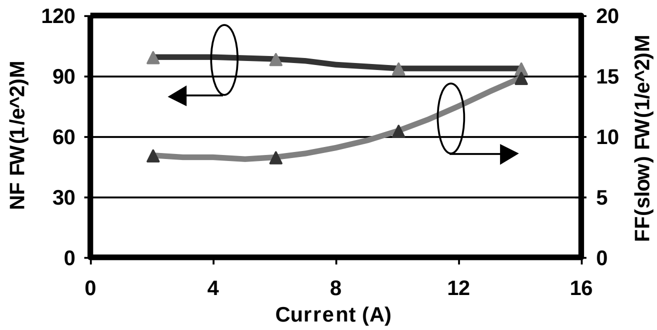

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Figure 2: (a) Typical slow axis and fast axis far field plots measured at 10A drive current, the fast axis far field FWHM is around 28° and FW1/e^2W is around 48°. (b) Typical lateral near field plots measured at 10A drive current. (c) Plots of the lateral near field FWHM width and slow axis far field FW1/e^2W vs laser diode injection current.

3. RELIABILITY RESULTS AND ANALYSIS

A laser diode lifetime can be described with the well-known bathtub curve, which includes an early failure period, a random failure period, and a wear-out failure period. The failure rates in the early failure period are typically due to assembly and major semiconductor defects but these weak devices can be screened out with a well-designed burn-in process. The wear-out failure period is characterized by an increasing failure rate at the end of a laser's life. In between early failure period and wear-out failure period is the random failure period, which represents diode's operation life with a relatively stable failure rate. Theoretically, the failure rate is a function of current, power and junction temperature, as indicated in equation (1), where I is current, P is power, T_j is junction temperature, m is the acceleration parameter of current, n is the acceleration parameter of power, E_a is the activation energy and k_B is Boltzmann constant..

$$FR \propto FR_0 I^m P^n \exp\left(\frac{-E_a}{k_B \cdot T_J}\right) \qquad (1)$$

In order to statistically estimate the device's failure rate under their use conditions, large numbers of devices have to be operated with long life-test duration. An alternative way is to conduct accelerated life-test with elevated current/power/temperature and use equation 1 to estimate the reliabilities at use conditions.

3.1 Step-stress life-test results

Step-stress life-tests at elevated currents/powers or temperatures were conducted to quickly guage laser reliability. Gen-*I* laser devices have been being life-tested with currents up to 14A at 50°C/80°C heat-sink/junction. Some groups have accumulated more than 15,000 hours of life-test duration, as in Figure 3. There are 9 each of 915nm and 980nm devices in Figure 3, with life-test current stepped from 9A to 14A and heat-sink/junction-temperatures kept at 50°C/80°C through the stress steps. As seen in the curves, only two devices have failed and no wear-out has been observed up to 15,000h accelerated life-test.

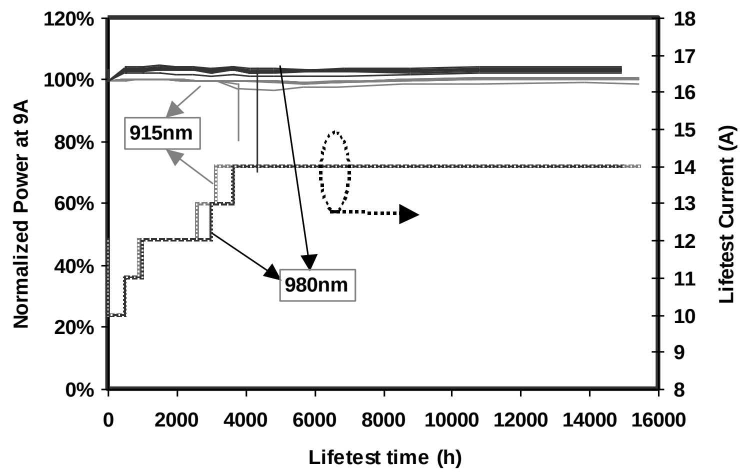
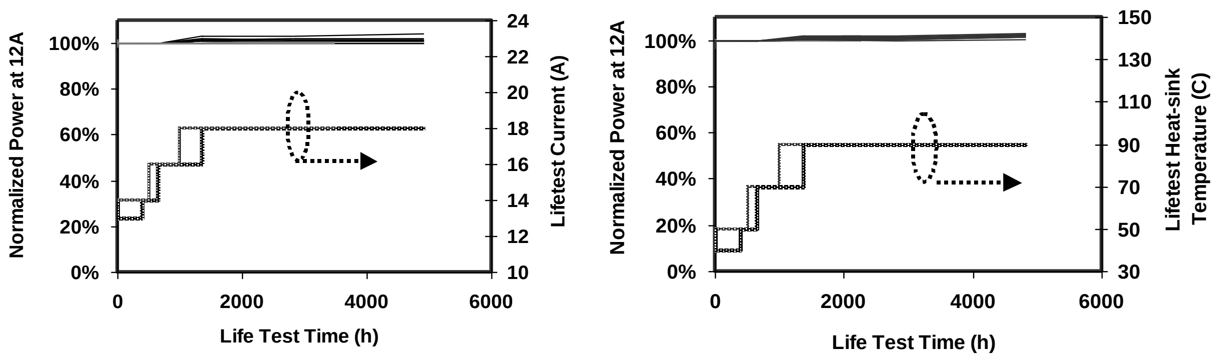


Figure 3: Stress life-test of Gen-*I* long laser diodes with life-test current stepped from 9A to 14A, and heat-sink/junction temperatures kept at 50°C/80°C at each stress step

Step-stress life-test has been conducted on Gen-*II* 980nm devices as well. One group of step-stress life-test was to accelerate current ranging from 14A to 18A while heat-sink/junction temperatures were kept at 50°C/75°C. The other group of step-stress life-test was to stress diode lasers with heat-sink/junction temperature ranging from 50°C/75°C to 90°C/115°, while current was kept at 14A. Each of the groups had 20 laser diodes. The life-test results are shown in Figure 4(a) and 4(b). No failures have been shown in these 40 laser diodes.



(a) (b)

Figure 4: (a) Step-stress life-test of Gen-*II* laser diodes with life-test current stepped from 14A to 18A, heat-sink/junction temperatures kept at 50°C/75°C (b) Temperature stress life-test of 3.8mm long laser diodes heat-sink/junction temperature stepped from 50°C/75°C to 90°C/115°C, with current kept at 14A

3.2 Multi-cell life-test design and results

In order to determine the acceleration factors and activation energy used in equation (1) and to verify the statistical distribution of device's reliability, a multi-cell life-test was designed and conducted on Gen-*II* diode lasers.

Multi-cell life-test is a relatively costly process, as long test durations and large device quantities are required to extract data with reasonable confidence. Designing a multi-cell life-test involves a compromise between "efficiency" and "extrapolation." For example, test plans with more stress levels are more robust than plans with fewer stress levels because they rely less on the validity of the life-stress relationship assumption. But test plans with fewer stress levels can be more convenient. In addition, other practical factors need to be considered in the multi-cell test plan, which include limited life-test channels, budget and time, as the life-test experiments usually need to be completed within 1-2 years or sooner. Device's performance capabilities and life-test equipment capabilities also set boundaries on the multi-cell design. In particular, temperatures and currents that result in thermal roll-over were avoided in our design.

Once cell levels are defined, failure rates at each level can be estimated based on previous life-test data, using nominal acceleration factors. In our multi-cell design stage, Monte Carlo simulations, with more than 500 trails, were performed to examine possible outcomes at statistical level for each experiment configuration. The simulations show that it would take about 10,000 hours and 200-300 units to get reasonable outcome (~35% uncertainty), if the device failure rate is near 2500 FIT. Finally a 7-level design was chosen, as shown in Table 1. The 7 levels can be broken into two subgroups. One subgroup has 4 current levels: 12A, 14A, 16A, and 18A, while junction temperature was fixed at 80 °C. The other subgroup has 4 junction temperature levels, 64°C, 80°C, 95°C and 110 °C, while the product of current and power was kept at ~186 AW. Such designs of the subgroups would allow more direct examination of power/current acceleration factors and activation energy.

Multi-cell 7-level lifetest						980nm		915nm	
Lifetest Group	**P(W)**	**I (A)**	**P*I**	**Junction T (C)**	**Heat sink T (C)**	**Units**	**Failure**	**Units**	**Failure**
1	15.9	18.0		80	52	10	1	2	1
2	11.3	12.0		80	62	40	1	10	0
3	14.6	16.0		80	55	18	0	6	0
4	13.0	14.0	182	80	58	21	0	3	0
5	11.9	15.7	186	110	88	12	1	3	0
6	12.6	15.0	189	95	73	18	1	6	0
7	13.6	13.7	187	64	42	47	0	12	0
Total						166	4	42	1

Table 1: 7-level multi-cell life-test design and results

A total of 208 devices were used in the 7-level design, with 166 devices at ~980nm and 42 devices at ~915nm. So far, this multi-cell life-test has accumulated ~7000 hour duration at each accelerated condition, as shown in Figure 5. First of all, none of the groups in Figure 5 has shown any slow degradation. Secondly, no wear-out has been observed under any of the conditions shown in Table 1. The multi-cell life-test has yielded ~1.3 million raw device hours. Only 5 failures have been found so far. All of them are sudden failures. The numbers of failures are listed in Table 1. As seen in the table, 4 out of 166 980nm devices have failed so far. Only one out of 42 915nm devices has failed. Obviously, acceleration factors and activation energy cannot be extrapolated meaningfully with good confidence, due to such low quantity of random failures. Thus, the failures are treated as random failures with exponential distribution and FIT scores will be estimated later in section 4.4.

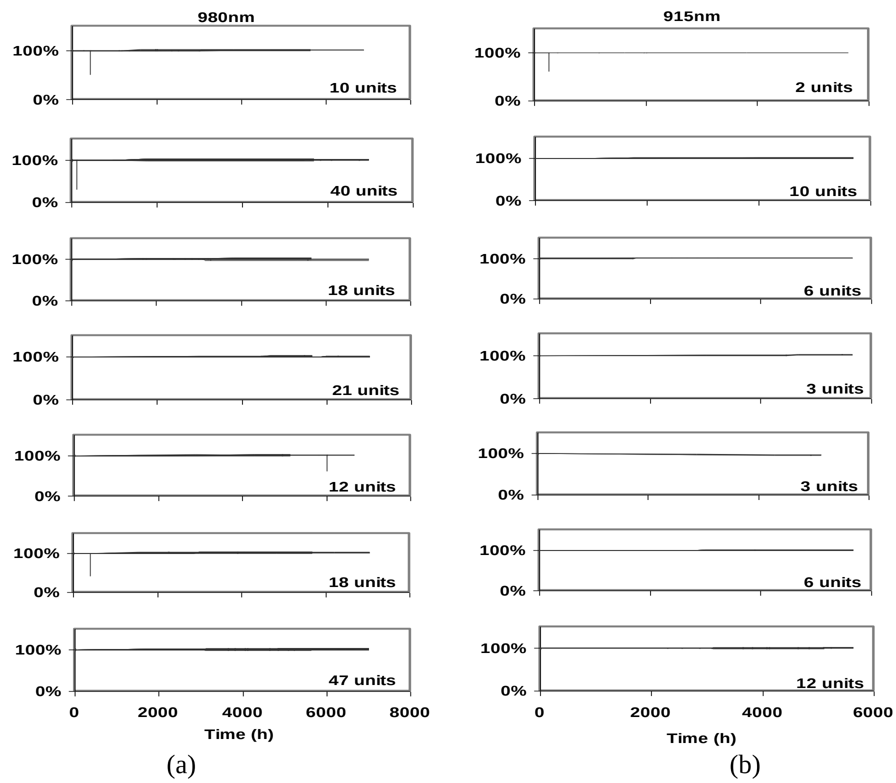


Figure 5: Multi-cell life-test plots and failures of (a) 980nm laser diodes (b) 915nm laser diodes. Y-axis is normalized power. From top to bottom, the subplots are multi-cell groups 1-7 as in Table 1

3.3 FAILURE MODE AND FAILURE ANALYSIS TECHNIQUES

Life-test failures and COMD test failures were studied with various techniques, including optical microscopy, electrical-luminescence (EL) imaging, photoluminescence (PL) microscope imaging, thermal imaging, SEM, EDX, SIMS and Auger. Two types of failure modes have been found to date.

The main failure mode at 9xx-nm is Bulk-defect initiated Catastrophic Optical Damage (BCOD). The bulk-defect could be an epi-grown defect or a process-induced defect during manufacturing process or handling. No COMD symptoms have been observed on facet or near facet for this failure mode. Typical pictures of BCOD can be seen as in Figure 6(a) and (b) as below. Figure 6(a) is a picture taken under optical microscope after die-shear. We observed COD traces of damaged areas originated from a defect highlighted in the circle. The defect in the circle was also magnified using SEM. In some cases, bulk defects may not be visible on the epi surfaces. In these cases, we investigated BCOD using photoluminescence (PL) microscopy, which is an infrared imaging technique, with shorter wavelength light used for pumping and PL signal used for imaging. In the PL microcopy image, Figure 6(b), the bulk defect was observed as a “dark” spot where the COD lines originated.

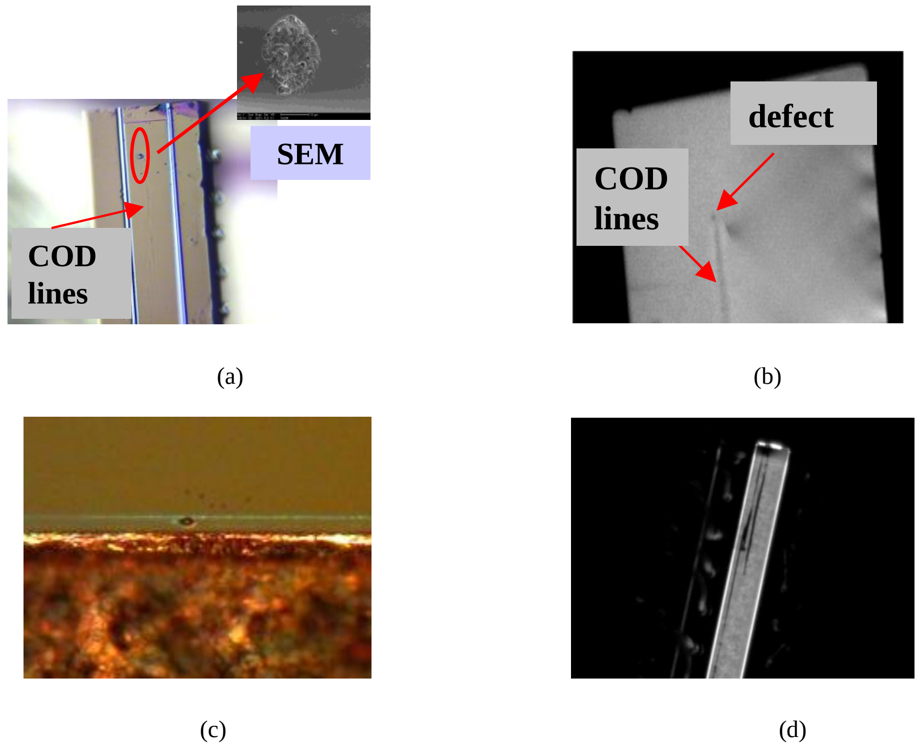


Figure 6: (a) Bulk-defect COD under optical microscopy (b) bulk-defect COD under PL microscopy imaging (c) COMD under optical microscopy (d) COMD under EL microcopy imaging

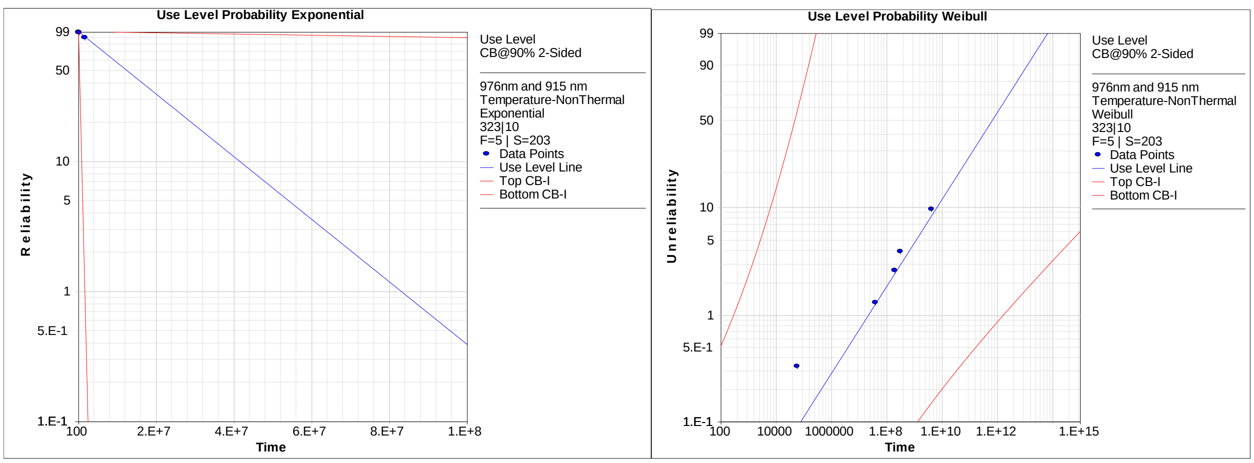
The second type of failure mode is Catastrophic Optical Mirror Damage (COMD). COMD starts with light absorbed at facet surface due to carrier-photon recombination at surface states generated by facet cleaving. These states cause local heating at facet and the semiconductor band-gap shrinks with higher temperature, which results in more surface recombination. Rapid temperature increase in this run-away process will eventually cause the semiconductor to melt and cause permanent physical/chemical damage to the laser. COMD has been found to be the main failure mode in 808nm diode lasers when they are working in the wear-out region of the bath-tub curve [11]. Typical pictures of COMD can be seen as in Figure 6(c) and (d). Figure 6(c) is a picture on facet taken under optical microscope. Figure 6(d) is an EL microcopy imaging, when current is put through failed device. As seen in this picture the COMD traces originate from the facet.

After indentifying BCOD as the main failure mode in 9xx diode laser life-tests, manufacturing processing control have been strengthened and burn-in conditions were optimized. Under Six-Sigma processing control and tough screening, failure rate in Gen-*II* 9xx-nm diode lasers has been further reduced.

3.4 RELIABILITY ANALYSIS

There are many different distribution models that can be used to analyze failure rates in diode laser life-test. Out of them, the three most commonly used distributions are exponential distribution, lognormal distribution and Weibull distribution. The exponential distribution is used for devices with constant failure rate, such as, the random failure period of diode laser. Failure rate in the random failure period is typically evaluated with a FIT (failures in 10^9 device-hours) score. Lognormal distribution and Weibull distribution are used for general reliability analysis, where failure rate is not constant, so the MTTF (Mean Time To Failure) or MTBF (Mean Time Before Failure) is typically reported. The accuracy of FIT or MTTF is commonly reported with confidence bounds. For diode laser devices, usually only upper confidence bounds are reported for FIT score, while only lower confidence bounds are reported for MTTF

With each distribution model, acceleration factors in equation (1) can be extrapolated using commercial software with confidence bounds. There are very limited data on the acceleration factors and activation energy from literature, especially for state-of-the-art high power diode lasers. For high power semiconductor lasers, E_a in the range between 0.41 eV to 0.64 eV have been reported [5-9], $m+n$ values ranging from 2.2 to 5.9 have been reported, for random sudden failure. For wear-out failures, E_a in the range between 0.41 eV to 0.53 eV have been reported [5-9], $m+n$ values ranging from 2.3 to 5.7 have been reported. Classic wear-out failure is slow degradation related, which is the main failure mode for long wavelength devices in 1300-1500 nm region. It is worth mentioning that parameters reported in the literature are based on very limited experimental trials, device numbers, device failure, life-test duration and type of devices. It has been strongly sought in the high power diode area to have much more life-test data for the statistical analysis and acceleration models. However, the same problems have been encountered here.



(a) (b)

Figure 7: (a) Use level reliability vs time with exponential distribution model, including 90% confidence bounds (b) Use level reliability vs time with Weibull distribution model, including 90% confidence bounds

The statistical analysis of the failures seen in multi-cell life-test so far were attempted, using exponential and Weibull distribution models [12], assuming m=0. The results are shown in Figure 7 (a) for exponential model fitting including 90% confidence bounds and in Figure 7 (b) for Weibull model fitting including 90% confidence bounds. Fitted parameters from either plot have huge uncertainties. In exponential distribution, n is estimated to be from –0.11 to 15, E_a is from –0.2eV to 0.9eV, with 90% confidence bounds. In Weibull distribution, n is estimated to be from –4.5 to 40, E_a is from –0.6eV to 2.4eV, with 90% confidence bounds. In other words, with such huge uncertainties, acceleration factors cannot be derived with any reasonable accuracy from either of the models, as there are too few failures. The only clear information we can derive from the plots is that the devices in multi-cell have not shown any wear-out, as the shape factor in Weibull distribution is close to 1 with 90% confidence.

Without meaningful experimental parameters, nominal values from literature, m=2, n=2, and E_a=0.45, were used to estimate lifetime and FIT scores at use conditions. Based on data from the 266 devices undergone stress life-test or multi-cell life-tests, 9xxnm Gen *II* devices achieved ~500 FIT, with 90% confidence, at 10W and 33°C/50°C heat-sink/junction temperatures. The equivalent $MTT_{10\%}F$ with 90% confidence level is about 25 years. As wear-out hasn't been observed in the life-tests, the onset of wear-out is estimated to be more than 44 years. For the two multi-cell groups at the least accelerating conditions, 12A/11.3W, 80°C and 13.7A/13.6W, 64°C, only one device out of 109 devices has failed so far. Assuming running at the same failure rates, it will take 10 years for these two groups to reach

10% failure. Hence, it is reasonable to state that it will take extremely long time to obtain meaningful acceleration factors, if the failure rate is kept the same.

4. CONCLUSION

A new generation of 915/980-nm diode lasers has demonstrated ever-increasing rollover power and improved laser performance. The key elements are design optimization, facet passivation and manufacturing process control, which are critical to reduce COMD and BCOD. BCOD was observed to be the main failure mode at random failure stage for diode lasers in 900-1000nm range. Multi-cell life-test is being conducted for current up to 18A and junction temperature up to 110°C. They have been running at 12-16W for more than 7000 hours, or 1.3 million total device hours with extremely low failure rate. This doesn't allow meaningful extrapolation on acceleration factors and activation energy. When nominal acceleration parameters from literature are used, approximately 500 FIT with 90% confidence is estimated for the 980nm and 915nm devices to operating at 10 W. The onset of wear-out of the devices is estimated to be more than 44 years of operation at 10W.

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