Reliability of High Power/Brightness Diode Lasers Emitting from 790 nm to 980 nm

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ABSTRACT

This paper presents recent progress in the development of high power single emitter laser diodes from 790 nm to 980 nm for reliable use in industrial and pumping applications. High performance has been demonstrated on diode lasers from 790 nm to 980 nm, with corresponding peak efficiency ~65%. Reliability has been fully demonstrated on high power diode lasers of 3.8 mm laser cavity at 3 major wavelengths. We report on the correlation between photon-energy (wavelength) and device failure modes (reliability). A newly released laser design demonstrates diode lasers with 5.0 mm laser cavity at 915-980 nm and 790 nm, with efficiency that matches the values achieved with 3.8 mm cavity length. 915-980 nm single emitters with 5.0 mm laser cavity were especially designed for high power and high brightness applications and can be reliably operated at 12 W to 18 W. These pumps have been incorporated into nLIGHT's newly developed fiber coupled pump module, element™. Ongoing highly accelerated diode life-tests have accumulated over 200,000 raw device hours, with extremely low failure rate observed to date. High reliability has also been demonstrated from multiple accelerated module-level lifetests.

Key words: Reliability, lifetime, lifetest, high power, high efficiency, 980 nm, 790 nm, semiconductor laser diodes, fiber-coupled modules

1. INTRODUCTION

There is an increasing demand for high power high brightness diode lasers from 790 nm to 980 nm, for applications such as fiber laser pumping, materials processing, solid-state laser pumping, and consumer electronics manufacturing [1-3]. The kilowatt fiber laser pumping particularly requires the diode lasers to have both high power and high brightness [4-7], to achieve high-performance fiber lasers with reduced manufacturing cost. In the last decade, the power and brightness of multi-mode diode lasers have improved by a factor of 5 roughly through increased cavity length and improvements in epitaxial design, facet passivation and heat-sink design. This tremendous improvement in diode laser brightness places tight constraints on the robustness and reliability of high power/brightness multi-mode diode lasers from 790 nm to 980 nm.

Over the last 5 years, we have continuously improved the power and reliability of high-brightness broad area diode lasers. Previously we reported high performance and high reliability on 915-980 nm and 790-815 nm high power diode lasers with 3.8 mm laser cavity [8-9]. In this report we demonstrate performance at 878-890 nm, with solid reliability data supporting the power rating. Failure modes following random and wear-out failure statistics will be analyzed with similarities and differences summarized. We also report on the improved power/brightness enabled by newly released chip designs with 5.0 mm laser cavity length. Epitaxial design from 980 nm to 790 nm has been re-optimized for longer laser cavity to preserve the high performance and to improve power/brightness, and we report on the initial results of highly accelerated life-test on these 9xx nm broad area laser diodes with 5.0 mm cavity length. The reliability of 3.8 mm cavity length diodes has been verified at the package level with accelerated life test results from 400-500W high power modules and VBG-locked modules. Paths for future improvements will also be discussed.

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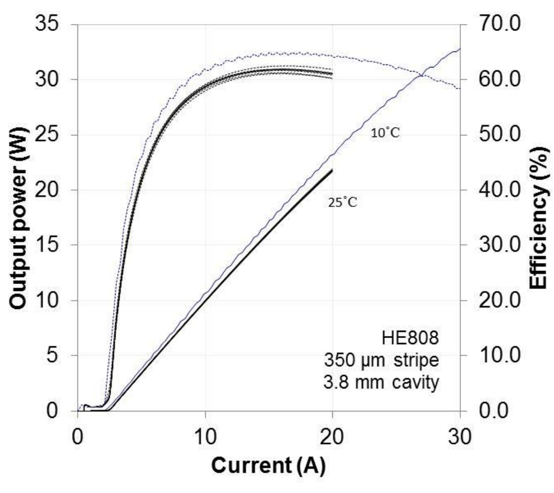
2. 790-980 NM DIODE LASERS WITH HIGH EFFICIENCY (HE) DESIGN

nLIGHT's 790-980 nm diode lasers are based on a high efficiency (HE) design with emphasis on improved reliable high performance with balanced performance metrics. The HE design is achieved on a hybrid material system with a super large optical cavity (SLOC) structure, which can be configured for reliable operation from 790 to 980 nm through device scaling. The SLOC design can greatly reduce optical power density on the facet, while achieving low internal optical loss, making it suitable for power scaling in long cavity length diode lasers. The epitaxial layers are grown by high quality Metal-Organic Chemical Vapor Deposition for extremely low defect density. The cleaved bars are processed with nLight's extended lifetime (*n*XLT) facet passivation. The chips are bonded p-side down with AuSn solder onto Aluminum Nitride (AlN) expansion-matched heatsinks.

2.1 High efficiency 3.8 mm cavity chip design with fully established performance/reliability

Over three years ago nLIGHT first reported on 95um wide 3.8 mm cavity length devices rated to 10 W at 915-980 nm. On these devices, we performed a multi-cell lifetest with 208 diode lasers from 915 to 980 nm [8]. Despite 2-year's efforts with an accumulation of 2.7M raw device hours, only 14 failures were observed. With such low failure rate there is still significant uncertainty in the extrapolated power acceleration and temperature acceleration factors. Multi-cell was then stopped as analysis shows the uncertainty would not narrow down by collecting more device hours on these devices. High performance 790-815 nm diode lasers of 3.8 mm cavity were subsequently reported [9]. For these devices the mode of failure was found to be different from 915-980 nm devices. However, we demonstrated high reliability at de-rated power compared to 915-980 nm diode lasers with same chip configuration. High power rating on this wavelength family can be achieved with devices with a wider emission area. Recently we successfully scaled power on devices with 350 µm wide stripes and 3.8 mm laser cavities, which are capable of reliable operation at 15W on a single emitter package. Figure 1(a) shows the typical power and efficiency of this 15W rated chip at ~810 nm. With a slope efficiency ~1.33 W/A, the chip reaches 15 W at only 14 A at 25 ˚C testing control temperature. LI is very linear at 25 ˚C operation and there is no visible power rollover up to 30A at 10 ˚C operation. High efficiency is preserved in this wide chip with peak efficiency of ~62% and operating efficiency close to 62% at 15 W 25 ˚C. The typical slow-axis and fast-axis far fields of this chip at 14A are shown in Figure 1(b). The FWHM and FW1/e^{2}W of the fast-axis far field are about 32 ^{o} and 54 ^{o} respectively. FWHM and FW1/e^{2}W of the slow-axis far field are about 7.9 ^{o} and 9.4 ^{o} respectively.



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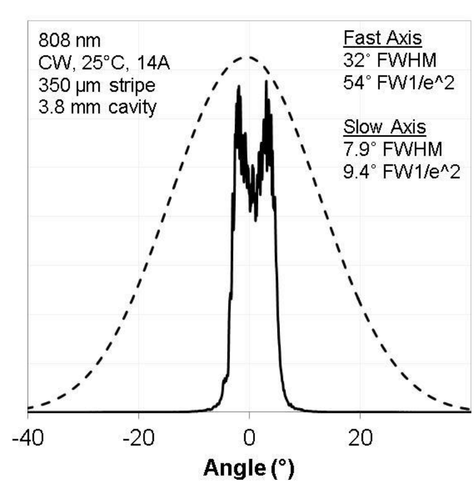
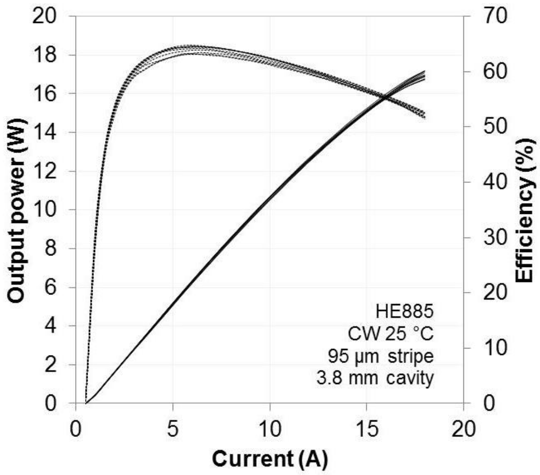


(b)

Figure 1: Performance of 15W 808 nm chip of 350 µm wide stripe and 3.8 mm long laser cavity (a) power and efficiency at 25 ˚C and 10 ˚C (b) fast-axis and slow-axis far field at 14 A (15 W).

nLIGHT's high efficiency (HE) design was also scaled to 878-890 nm. The typical Light-current (LI) and wall-plug efficiency of HE devices emitting at ~88x nm are shown in Figure 2(a), at 25 ˚C test station control temperature. As seen in Figure 2(a), these HE 88x nm diode lasers with 95 µm stripe widths and 3.8 mm cavity lengths have thresholds ~ 0.6 A and slope efficiencies ~ 1.18 W/A. The peak wall plug efficiency of these HE devices is about 65%, which is as high as our 915-980 nm lasers [8]. At 6 W operation condition, the operation current is around 5.8 A, and 6 W wall plug efficiency is close to 64%. The high efficiency performance has been achieved for a wide wavelength range for HE 88x nm lasers. As seen in Figure 2(b), wall plug efficiencies at 6W and 25 ˚C operation is ~64%, for devices from 875 nm to 888 nm. Generally, the HE 88x nm devices show CW power rollover levels of about 20W at 10˚C operation, without any Catastrophic Optical Mirror Damage (COMD) failure, as shown in Figure 2(c). The results are consistent and similar to what we found on HE 915-980 nm diode lasers [8], despite higher photon energy (shorter wavelength). The slow-axis and fast-axis far fields of the HE 88x nm devices at 10 A are shown in Figure 2(d). At 7 A, the FWHM and FW1/e^{2}W of the 88x nm device fast-axis far field are about 28 º and 46 º respectively. FWHM and FW1/e^{2}W of the slow-axis far field are about 5.6 º and 6.4 º respectively. The reduced far field improves optical fiber coupling efficiency by reducing the launch NA of light incident on the delivery fiber.



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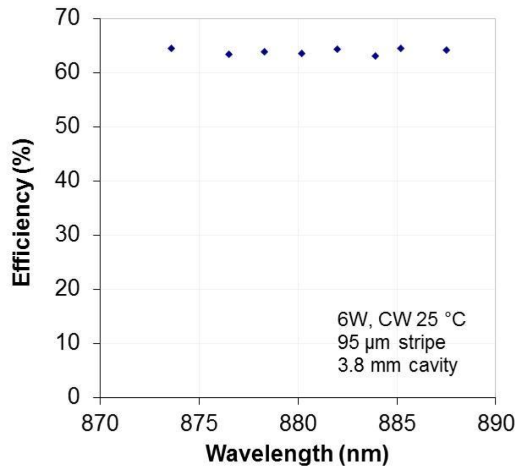

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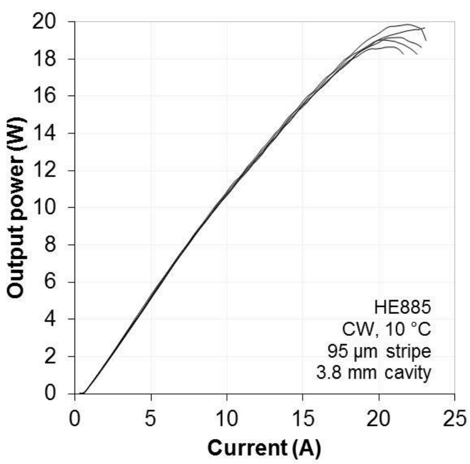

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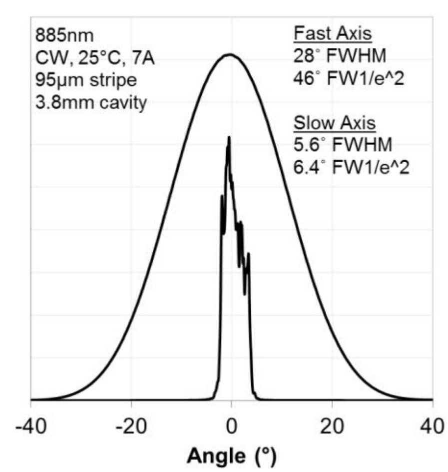


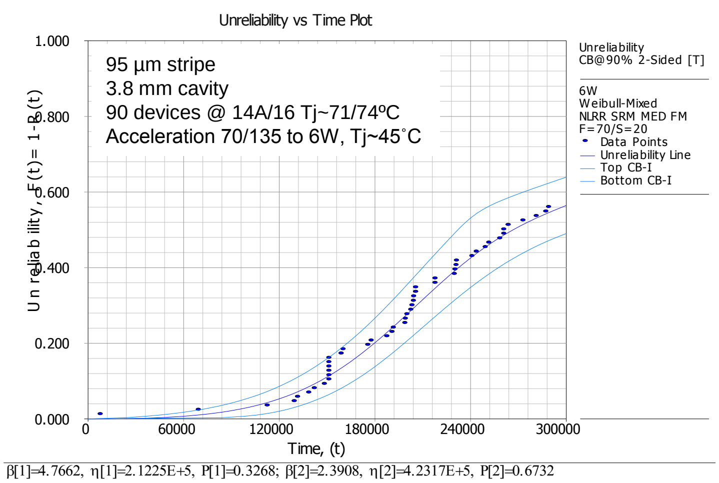
(d)

Figure 2: HE 88x nm lasers of 95µm stripe width and 3.8mm cavity length (a) typical power and efficiency at CW 25°C (b) efficiency versus wavelength at 6W 25°C (c) CW tested to rollover at 10°C (d) typical far field at 7A

To qualify 88x nm devices, a total of 90 88x nm lasers of 95 µm stripe width have been loaded for accelerated lifetest at 14/16 A and 71/74 ˚C junction temperature, and a total of 60 88x nm lasers of 200µm stripe width have been loaded for accelerated lifetest at 18 A and 87 ˚C junction temperature. Similar to 915-980 nm devices in multi-cell, the initial incidence of random failure rate is also very low for 88x nm devices. Unlike the 9xx nm devices observed in [8] we observed device wear-out for 88x nm devices under these high accelerations, similar to what was previously observed on 780-815 nm devices [9]. Thus reliable power rating of 88x nm devices were also limited by the earliest wear-out observed so far and would be then less than what we rated on 915-980 nm chips with the same chip configuration. Currently 88x nm device of 95 µm stripe width is rated at 6W and 88x nm device of 200 µm stripe width is rated at 10W. For 88x nm device of 95 µm stripe width, the calculated acceleration factor at 14A and 16A is ~70 and ~135 separately for 6W T_j ~45C (25˚C test station) operation, using nominal parameters from literature, *m*=2 for current, *n*=2 for power, and E_a=0.45 eV for activation energy in equation (1) below. Similarly for device of 200 µm stripe width, the calculated acceleration factor at 18 A is ~30.6 for 10W T_j~57C (25˚C test station) operation.

$$\text{Acceleration Factor} \propto I^m P^n \exp\left(\frac{-E_a}{k_B \cdot T_J}\right) \tag{1}$$

The reliabilities of HE 885 nm lasers are then analyzed by fitting with the best distribution model [10], shown in Figure 3(a) and 3(b) for 95 µm stripe devices and 200 µm stripe devices. Each device failure is shown as an individual dot and the curves representing upper and lower 90% confidence bounds centered on the 50% confidence line. Wear-out on-set of each lifetest group is clear from the plot. Thus the reliability is better analyzed with a Mixed-Weibull as in Figure 3(a) for 95 µm stripe 88x nm devices, and 2-parameter Log-logistic distribution as in Figure 3(b) for 200 µm stripe 88x nm devices. The overall wear-out onset is determined by the earliest wear-out lifetest group in each plot. For both device configurations, the earliest wear-out onset is beyond 11 years so it would not be a reliability concern at the rated power operation. Figure 3(a) indicates with 90% statistical confidence, 95 µm stripe 88x nm device will have 95% population survive more than 11.1 years at 6W room temperature operation. Figure 3(b) shows with 90% statistical confidence, 200 µm stripe 88x nm device will have 95% population survive more than 9.3 years at 10 W room temperature operation.



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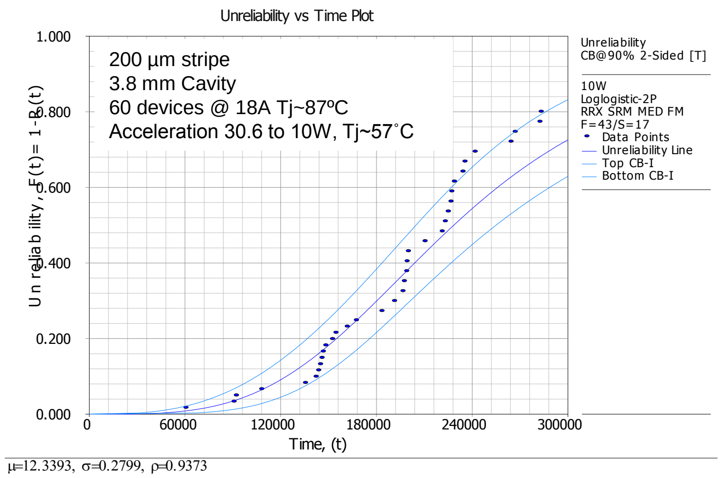


(b)

Figure 3: Unreliability analysis with 90% confidence of (a) 88x nm devices with 95 µm stripe and 3.8 mm cavity (b) 88x nm devices with 200 µm stripe and 3.8 mm cavity

A variety of failure mode analysis techniques were used to determine the failure mode of 88x nm devices. Similar to 915-980 nm and 790-815 nm devices, Catastrophic Optical Mirror Damage (COMD) and Bulk Catastrophic Optical Damage (BCOD) are the two most prevalent failure modes for random failures. In terms of failures at wear-out regime, we observed two types of wear-out failures. One is the COMD wear-out, which is not a surprise to us as we have observed and reported it on high power 790-815 nm devices [9]. It is the only wear-out failure we observed on 790-815 nm devices and it is believed that COMD is photon energy dependent and power density related. But the 2nd wear-out failure is new, which is a slow degradation wear-out. Not every failure showed slow degradation. The device with slow degradation was likely caused by lot/process variation which should be fully eliminated with a better control of the process once the root cause is determined.

Table 1 provides an overview of the performance and reliability of fully released 790-980 nm products with HE epi design on 3.8 mm cavity chip. 915-980 nm devices have the highest reliably rated power as a result of low failure rate and no wear-out limitation. 878-890 nm devices and 790-815 nm devices have to be de-rated for the same chip configuration, and are limited by the earliest onset of the wear-out failure mode. Our reliability data suggests a photon-energy dependent reliability and thus rated power/brightness from 990 nm to 790 nm. Improved reliability and rated power/brightness can be achieved by further optimization on epitaxial growth and facet passivation.

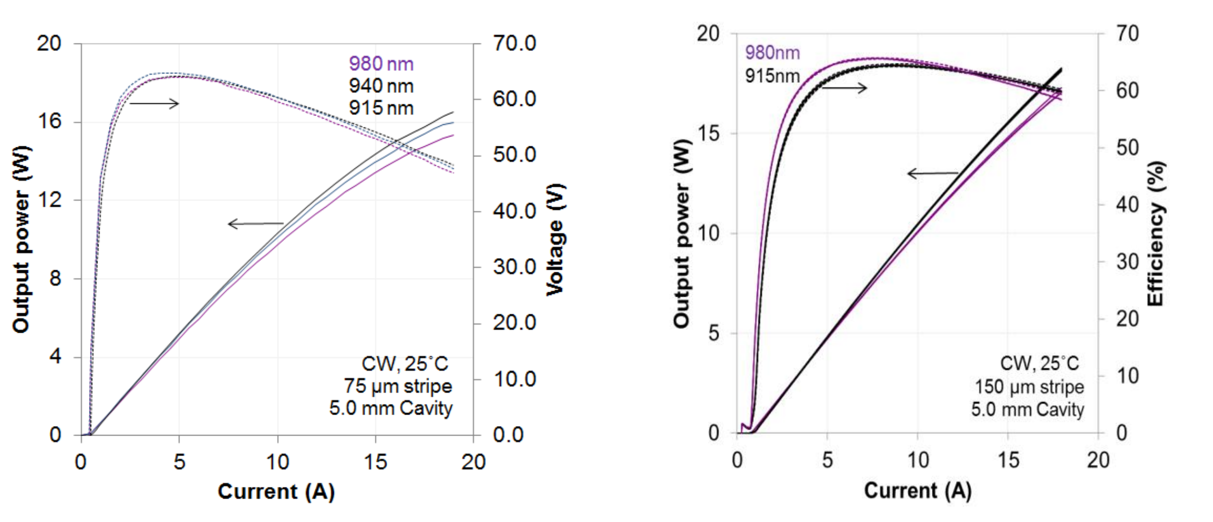
Chip Key Parameters	95 µm 3.8 mm Chip	95 µm 3.8 mm Chip	200 µm 3.8 mm Chip	95 µm 3.8 mm Chip	200 µm 3.8 mm Chip	350 µm 3.8 mm Chip
Wavelength	910-990 nm	878-890 nm		790-815 nm		
Rated Power	10W	6W	10W	5W	8W	15W
Peak efficiency	65%	65%	65%	65%	63%	62%
B05 (90% C.L.)	>12.4 years	>11.1 years	>9.3 years	>9.7 years	>7.5 years	Predicted > 7 years

Table 1: Performance and reliability of fully released 790-980 nm diode lasers with HE epi design on 3.8 mm cavity

2.2 New 5.0 mm cavity chip design with higher power/brightness

Recently nLIGHT has focused on optimizing HE design on chips with longer cavity length scaling to further improve power and device brilliance. These long devices improve the device rated power by reducing current density and lowering the junction temperature. What's more, it is well know the slow axis far field of the broad area laser can be reduced with longer laser cavity [11]. Simply extending cavity length with our 3.8 mm chip epi design (R02) did not get the best performance on 5.0 mm chip due to the lower reduced slope efficiency and lower CW rollover power. Thus a thorough multi-parameter epi design DOE campaign was conducted to re-optimize the HE design specifically for 5.0 mm long devices. The newly optimized HE epi design can improve slope and rollover power by ~10% on a high brightness chip with 75 µm stripe width and 5.0 mm cavity length. We found the performance did not keep improving on chips with >5.0 mm cavity due to the finite intrinsic loss and longitudinal spatial hole burning [12].

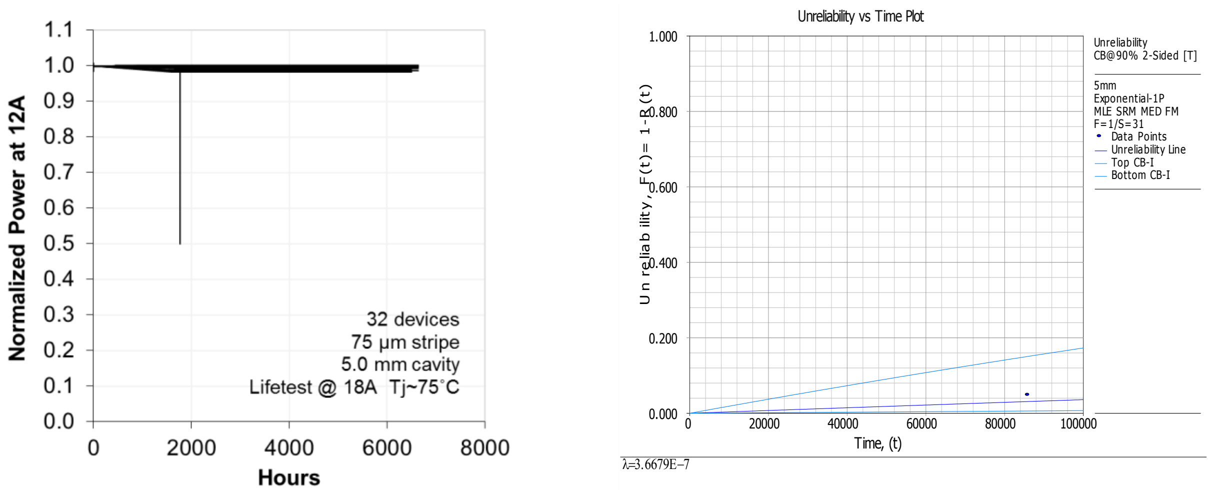
Figure 4(a) shows the typical power and efficiency the 915-980 nm devices of 75 µm stripe width and 5.0 mm cavity length. The slope efficiency represents scaling of photon energy while peak efficiency is still preserved at ~65% at 25 ˚C CW operation. The 75 µm emitter width was particularly chosen for 100 µm fiber-coupled modules with very low NA [13]. Based on reliability results from the 3.8 mm cavity devices, these devices of 75 µm wide stripe and 5.0 mm long cavity can be reliably rated at 12 W. Further power scaling can be achieved with increasing chip emitter stripe width. As shown in Figure 4(b), the 9xx nm devices of 150 µm stripe width and 5.0 mm cavity length can be tested almost linearly to close to 20A and they are good for rated 18W reliable CW operation.



(a) (b)

Figure 4: Typical continuous wave (CW) optical power and wall-plug efficiency verses drive current for 5.0 mm long 915/940/980 nm devices operating at 25°C (test station), with (a) 75 µm wide stripe, (b) 150 µm wide stripe

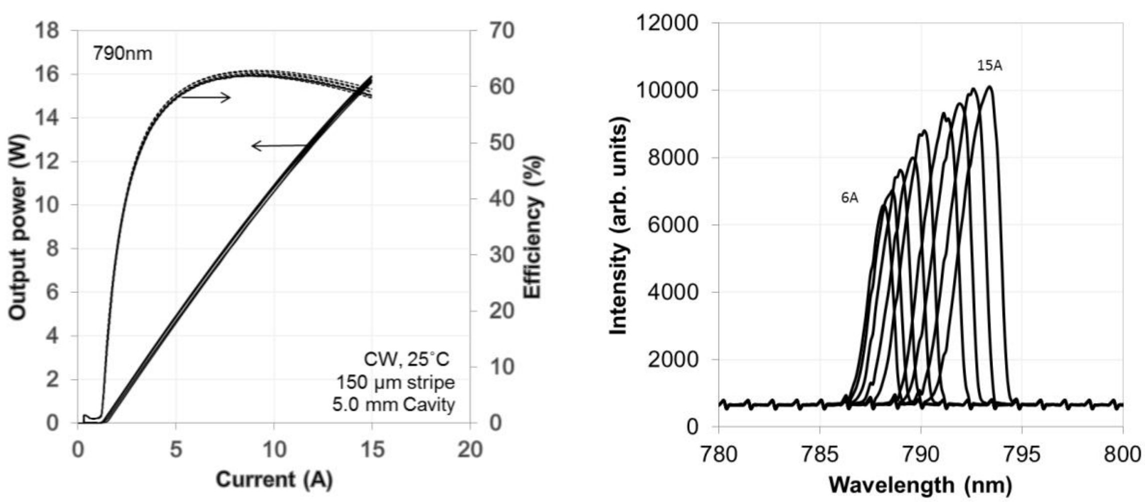
A total of 32 9xx nm lasers of 75 µm wide stripe and 5.0 mm long cavity have been loaded for accelerated lifetest at 18 A and junction temperature Tj~75 ˚C. As shown in Figure 5(a), only one random failure was observed by ~6000h with accumulated raw device hours close to 200,000 h. The failure is still too low to predict reliability (or failure rate) with high certainty. The exponential fitting [10] of the data suggest FIT~400 with 50% confidence and FIT<2000 with 90% confidence for 12W room temperature (Tj~52 ˚C) operation, as shown in Figure 5(b).



(a) (b)

Figure 5: Lifetest of 9xx nm devices of 75 µm stripe width and 5.0 mm cavity length (a) only 1 failure from 32 devices lifetested at 18A Tj~75 ˚C (b) reliability analysis with 2-parameter exponential distribution

New HE epi design optimization was also demonstrated on 790 nm devices of 5.0 mm cavity length. Typical performance of 790 nm devices of 150 µm wide stripe and 5.0 mm long cavity is shown in Figure 6. I_{th} of these devices is ~ 1.2 A and slope efficiency is ~1.30 W/A. The peak efficiency is ~62% at 25 ˚C CW operation. Such devices can be reliably rated at 10W based on reliability demonstrated from 3.8 mm devices. The devices reach 10W at ~ 9.3A at 25 ˚C CW operation. Spectral width as a function of drive current is shown in Figure 6(b). Spectral width FWHM and FW1/e^2 is around 1.7nm and 2.7nm at 10A. Further power improvements can be achieved on devices of 350 µm stripe width, which can potentially scale from 15 W rated power on 3.8 mm cavity (as shown in Figure 1) to ~17 W rated power on 5.0 mm cavity.



(a) (b)

Figure 6: Typical performance of 790 nm device with 150 µm stripe width and 5.0 mm cavity length, (a) continuous wave (CW) optical power and wall-plug efficiency verses drive current, (b) spectrum

Based on the above results we have demonstrated improved performance for 5.0 mm cavity length devices at 9xx nm and 790 nm with re-optimized HE epitaxial designs improving the reliable high-power operation of these devices. While the reliability of 5 mm CL diodes has yet to be experimentally verified, the initial accelerated lifetest results provide confidence in the overall reliability of these devices. Table 2 is a summary of the performance and the rated power of these next-gen high power/brightness devices with 5.0 mm cavity length.

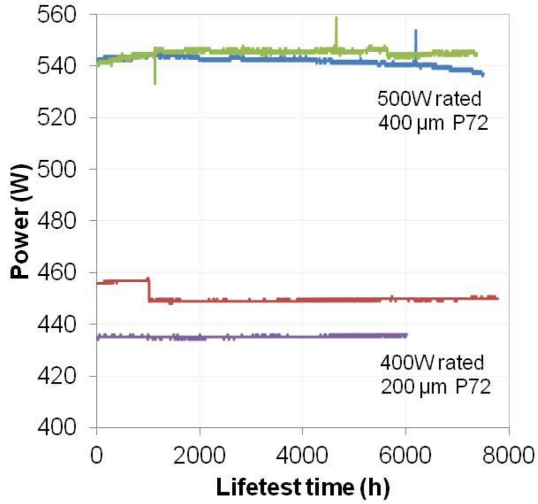
Chip Key Parameters	75 μm 5.0 mm Chip	150 μm 5.0 mm Chip	150 μm 5.0 mm Chip	150 μm 5.0 mm Chip	350 μm 5.0 mm Chip
Wavelength	910-990 nm		878-890 nm	790-815 nm	
Rated Power	12W	18W	12W	10W	17W (under dev.)
Peak efficiency	65%	65%	65%	63%	62%

Table 2: Performance and the rated power summary of the next-gen new high power/brightness devices from 980 nm to 790 nm

3. HIGH PERFORMANCE FIBER-COUPLED MODULES

High power reliable 3.8 mm cavity single emitter lasers in Table 1 are designed for efficient integration into nLight's compact, passively-cooled Pearl™ fiber-coupled module architecture [14-16]. The higher power/brightness 5.0 mm cavity single emitter lasers in Table 2 are especially developed for our newly released higher brightness, more compact element™ fiber-coupled module architecture [13]. In both cases, each laser is individually collimated in the fast axis and slow axis and free-spaced coupled into a single fiber, to scale the output power while maintaining the single emitter brightness. Besides the scaling of power and brightness in the Pearl™ module, the reliability of the module is also further improved from the high reliable single emitter diode lasers by effective redundancy [9].

Single-emitter based Pearl™ modules can provide as high as 400W from a 200 µm core fiber, or 500W from a 400 µm core fiber, with 72-emitters optically coupled inside. The high reliability was also verified on module level lifetest, as shown in Figure 7(a). 2 400W module were lifetested at ~450W and 2 500W modules were lifetested at ~550W. Only 1 chip failure out of 288 chips was found by 7000 h. The 88x nm Pearl™ modules with VBG locking were also evaluated with accelerated module lifetests as shown in Figure 7(b) and (c). Figure 7(b) shows the lifetest results of 60W rated module under fixed current (~80W) lifetest. There is no single chip failure out of the 5 modules (40 chips). VBG-locked 88x nm modules were also lifetested with step-current/power (11/12/13/14/15/16A) lifetests as shown in Figure 7(c). In this step-current/power lifetest, 3 chip failures were observed. However there were no module failures (defined as >20% power drop) as each dead chip belonged to a different module.



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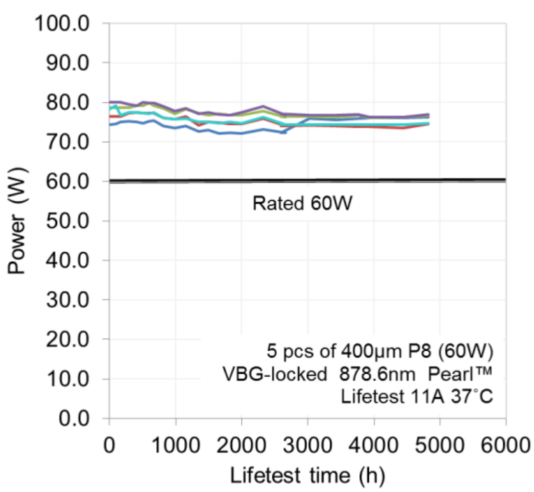

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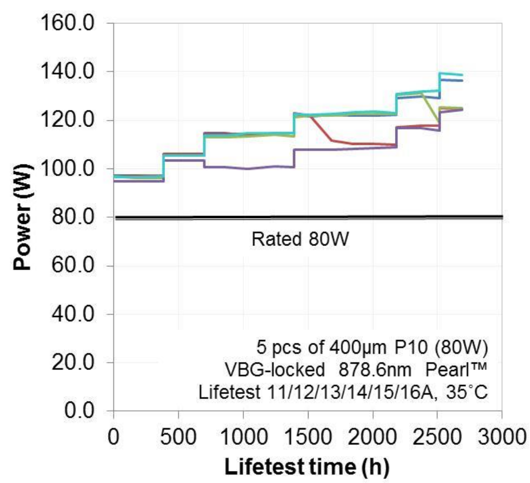

(c)

Figure 7: Module lifetests (a) 2 400W P72 at ~450W and 2 500W P72 lifetested at ~550W (b) 60W VBG locked 88x nm module lifetested at fixed current (11A, ~80W) (c) 80W VBG-locked 88x nm modules lifetested at step-current/power (11/12/13/14/15/16A)

The newly developed higher brightness, more compact element™ module is capable of 60W output from a 100 µm with very low NA (~0.13), utilizing the 5.0 mm cavity lasers. The key results are summarized in a different publication [12]. Accelerated module-level lifetests are on-going.

4. CONCLUSIONS

In summary, we present recent progress in the development of high power/brightness single emitter laser diodes from 790 nm to 980 nm for reliable use in industrial and pumping applications. High performance and reliability have also been extended to the 88x nm ranges, with a corresponding peak efficiency value in excess of 65%. Similarities and differences between high power diode lasers at 3 major wavelengths are summarized. It confirms a photon-energy (wavelength) dependence of failure modes and reliability. A newly released laser design demonstrates near-penalty-free performance on 5.0 mm long laser cavity diodes at 9xx nm and 790 nm. 9xx nm single emitters with 5.0 mm long laser cavity were especially designed for higher power/brightness and can be reliably operated 12 W to 18 W for newly developed higher brightness, more compact fiber-coupled element™. The ongoing highly accelerated life-test has accumulated over 200,000 raw device hours, with only 1 failure observed to date. Reliability data on 5.0 mm long devices are yet to be established but we can scale from the high reliability that have been fully established on 3.8 mm cavity length chips to 5.0 mm cavity chips with high confidence.

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