# High Reliability of High Power and High Brightness Diode Lasers


M. Kanskar*, L. Bao, J. Bai, Z. Chen, D. Dahlen, M. DeVito, W. Dong, M. Grimshaw, J. Haden, X. Guan, M. Hemenway, K. Kennedy, R. Martinsen, J. Tibbals, W. Urbanek, S. Zhang

*n*Light Corporation

5408 NE 88th Street, Bldg. E

Vancouver, WA 98665, USA



## ABSTRACT

We report on continued progress in the development of high power and high brightness single emitter laser diodes from 790 nm to 980 nm for reliable use in industrial and pumping applications. High performance has been demonstrated in nLIGHT's diode laser technology in this spectral range with corresponding peak electrical-to-optical power conversion efficiency of ~65%. These pumps have been incorporated into nLIGHT's fiber-coupled pump module, *element*™. We report the latest updates on performance and reliability of chips and fiber-coupled modules. This paper also includes a new chip design with significantly narrower slow-axis divergence which enables further improved reliable power and brightness. Preliminary reliability assessment data for these devices will be presented here as well.



**Key words**: Diode reliability, fiber-coupled diode laser, high brightness, pump diodes, diode laser brilliance, diode lifetime, life-test.


## 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, defense applications and consumer electronics manufacturing [1]. The kilowatt CW fiber laser pumping (915 nm - 976 nm) particularly requires the diode lasers to have both high power and high brightness [2-6] in order to achieve high-performance with reduced manufacturing cost. Although brightness is not as demanding for pumping solid-state lasers and gas lasers, the demand for higher power, better reliability and lower cost pumps continue to rise. As the power and brightness of pump diodes continue to improve, there is also a growing trend towards migrating from using bars to fiber-coupled diodes. In the past decade, the amount of power coupled into a single 105 µm fiber has increased by over a factor of 10 through improved diode laser brilliance and the development of techniques for efficiently coupling multiple emitters into a single fiber [7-8]. This paper presents nLIGHT's most recent efforts at engineering broad area diode lasers optimized for brilliance and output power for fiber-laser and solid-state laser pumping. We will detail power and brightness improvement along with preliminary reliability of these diodes at the chip and fiber-coupled module level.

## 2. DIODE LASERS WITH IMPROVED SPATIAL BRIGHTNESS AND OUTPUT POWER

### High Brightness 9xx nm Diodes

Single emitter broad area lasers (BALs) are the building block for pump modules for industrial and defense fiber laser systems due to their high brightness, excellent reliability, low production cost, and high optical-to-optical efficiency when implemented into multiple emitter fiber-coupled pump modules. Over the past several years, nLIGHT has continuously improved output power and brightness of laser diode chips by optimizing the cavity length and emitter width, primarily enabled by lower-loss epitaxial structures. For example, nLIGHT's 9xx nm devices with a 95 µm emitter width and 3.8 mm cavity length produced a rated output power of over 10W at an electrical-to-optical power conversion efficiency of >60%, while maintaining a failure-in-time rate (FIT) of <500 at 90% confidence level [9-10]. nLIGHT subsequently developed <0.5 $cm^{-1}$ loss epitaxial structures. This enabled fabrication of even longer cavity length (5 mm) devices with narrower emission width (75 µm) thus providing 12W rated output power and >60% power conversion efficiency. Reliability of these devices will be detailed below.


* manoj.kanskar@nlight.net; phone 360.553-9694; http://www.nlight.net

Although, higher power operation is possible from these low-loss devices, useful brightness scaling has been limited to 12W output power. Beyond this power, a rapid increase in slow-axis divergence limits useful fiber-coupled power. Historically, the efforts for improving the slow-axis brilliance of broad area diode lasers have been on lowering the slow axis divergence [12]. These techniques are typically focused on increasing the cavity length [11], reducing the lateral index contrast, and improving the thermal resistance to reduce the thermal lens [11]. These past effort produced some modest improvement but any significant performance improvement has saturated.

We have designed a new type of broad area laser called Reduced-Mode-diode (REM-diode) that allows us to further scale up in slow-axis brilliance. We achieve this by reducing the thermal lensing effect as well as reducing the permissible number of modes in the slow-axis direction. To study the improvement in slow-axis brilliance, nLIGHT fabricated 915 nm and 980 nm diode lasers that are based on a high efficiency epitaxial design. The high efficiency design is achieved on a hybrid material system with a super large optical cavity (SLOC) structure which reduces optical power density on the facet (in the fast-axis direction) while achieving low internal optical loss. This SLOC design has an optimized doping profile to balance the effects of intrinsic optical loss and series resistance. 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. nLIGHT fabricated devices with a range of emitter widths in this study. For comparison purpose, we will refer to the current brightest chip, 75 µm × 5 mm device, as the standard. Typically, the REM-diodes display lower slow-axis divergence. This allows us to operate REM-diodes with larger emission width resulting in larger area. This has several positive attributes. First, the thermal footprint of these devices is larger making the thermal resistance lower. Consequently, the rollover power is higher for these devices at the same beam parameter product. Furthermore, the series resistance is lower. As a result, the efficiency of these devices does not drop off as quickly as the standard devices. Each of the devices was optically screened prior to bonding p-side down with AuSn solder onto Aluminum Nitride (AlN) expansion-matched heatsink. The devices were characterized in terms of output power, near-field profile and far-field divergence. This information was then used to extract the slow axis brilliance as a function of output power, and the beam parameter product (BPP) as a function of output power.

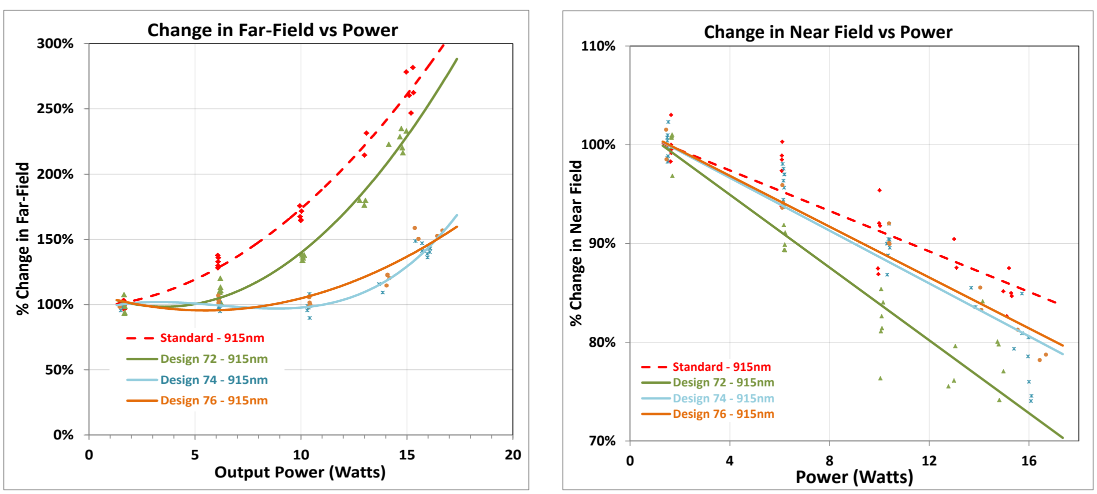


**Figure 1:** (a) Change in slow-axis far-field of a standard device compared to three different designs of REM-diodes with varying emission widths. In all cases, the slow-axis divergence is smaller compared to the standard device and the change in far-field as a function of output power is also smaller. (b) Plots showing reduction in near-field for standard devices as compared to REM-diodes over a range of operating powers.

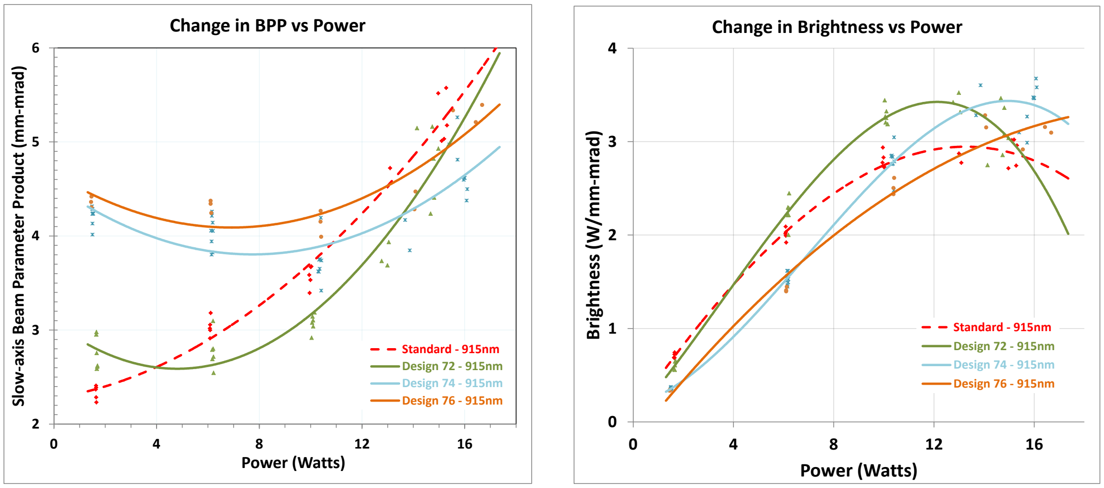


**Figure 2:** (a) Plot of slow-axis BPP as a function of output power and (b) plots of slow-axis brightness as a function of output power for standard and REM-diodes.

The first remarkable feature about REM-diodes is that the slow-axis divergence remains approximately constant over a larger operating power range and increases only when diode temperature approaches onset of thermal rollover as shown in Figure 1(a). For example, around 15-16W of output power, slow-axis divergence increases approximately three times for a standard device. It is typically only half that for the REM-diodes. In general, all the designs studied so far produce lower divergence angles compared to the standard device. Divergence angle increases at a slower rate as the operating power increases. This demonstrates the efficacy of our technique in limiting the number of allowed lateral modes. It was also observed that the near-field profile typically would decrease by ~15% for the standard device when the output power increases. However, the near-field for REM-diodes decreases by ~20% to 30% as shown in Figure 1(b). A combination of significantly smaller slow-axis divergence and more enhanced near-field reduction, allows devices with larger emission aperture than was possible in the past to meet a given beam-parameter product requirement. nLIGHT has performed a design of experiments to achieve a minimum BPP at the maximum possible output power. Figure 2(a) shows beam parameter product (BPP) as a function of power for three REM-diode designs in comparison with the standard device. A standard device achieves a BPP of ~4.3 mm-mrad (required for 105 µm/0.15 NA fiber) [12] at an output power of ~12W. One of the REM-diode designs (Design 74) shows ~15W output power at the same BPP. Furthermore, the BPP for this device is relatively flat across the operating power. The slow-axis brightness for these devices is plotted in Figure 2(b). The best design shows a peak brightness of ~3.6 W/mm-mrad at 15W; whereas, standard device has a peak brightness of ~3 W/mm-mrad near 12W. This brightness enhancement results from a combination of improvement in output power and reduction in slow-axis BPP.

Figure 3(a) shows a typical power and efficiency of the 9xx nm devices with 75 µm stripes and 5.0 mm cavities in comparison with several of the REM-diode designs. Though Designs 72, 74 and 76 all demonstrate higher brightness, Designs 74 and 76 clearly show higher output power from approximately 10A to 18A. The electrical-to-optical power conversion efficiency of these devices is also higher in this current range. Since higher power is generated from larger areas i.e. wider emitters, both the current density and the facet power density can be matched or lowered compared to past device designs that have a proven reliability. Consequently, we expect the reliability of these new designs to be on par or slightly better. Preliminary reliability of these devices looks very promising and will be shown in the following section under reliability assessment.

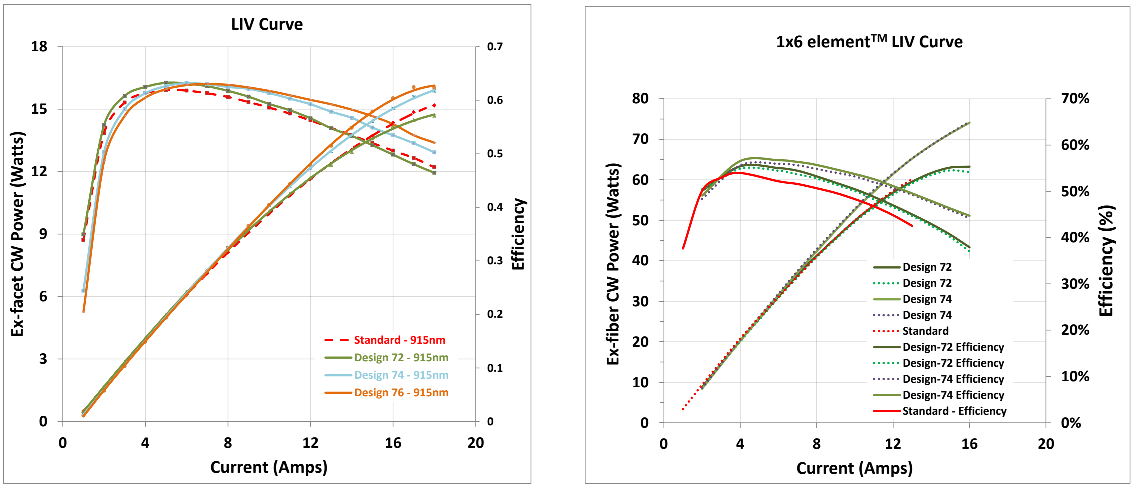


**Figure 3:** (a) Typical continuous wave (CW) ex-facet optical power and electrical-to-optical power conversion efficiency versus drive current of 9xx nm devices operating at 25°C for standard and REM-diode lasers. (b) (CW) optical power and electrical-to-optical power conversion efficiency versus drive current for 1×6 *element*™ using standard and higher brightness REM-diode chips of Design 72 and 74 coupled into105 µm/0.15 NA.

### High Brightness 790-820 nm Diodes

Over the past six years, we have continuously improved the power without sacrificing reliability of high brightness broad area diode lasers in the 790 nm to 980 nm range. In the past we reported on the 3.8 mm laser cavity length devices in the wavelength range of 790-820 nm. Here we report progress on higher power 5 mm cavity length devices. Figure 5(a) shows the typical power and efficiency of the ~790 nm 10W-rated chip. With a slope efficiency ~1.3 W/A, the chip reaches 15 W at only 14 A at 25 °C. High efficiency is achieved in this chip with peak efficiency of ~62% and operating efficiency close to 60% at 15 W at 25 °C. Spectral response between 6A and 15A is shown in Figure 5(b) and the spectral width remains under 2.1 nm till 15A.

A wider chip with 350 µm emission aperture and 17W-rated power is under development. Furthermore, REM-diodes in the 790-820 nm are also being evaluated and results will be published in the near future.

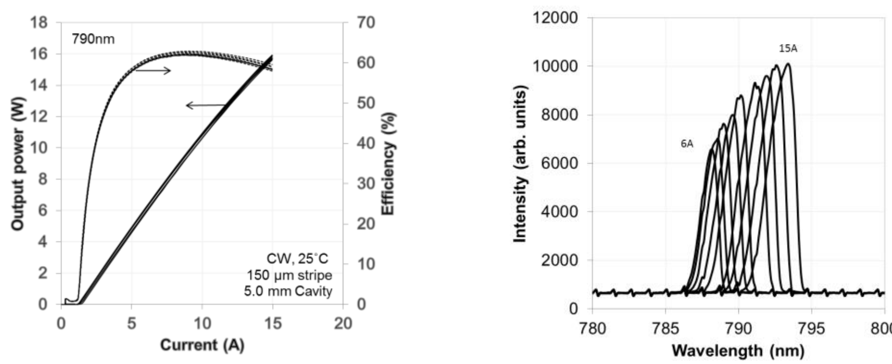


**Figure 5:** (a) The CW LIV and efficiency of 10W 790 nm 150 µm × 5 mm laser diode. (b) Spectra in the 2A to 15A operating current range demonstrating less than 2.1 nm FWHM up to 15A.

## 3. HIGH PERFORMANCE FIBER-COPUPLED MODULES OPTIMIZED FOR BRIGHTNESS AND POWER

The standard high power and high brightness 5.0 mm cavity single emitter lasers were developed for our *element*™ fiber-coupled module architecture with 60W output power from a 1×6 emitter configuration [12]. Each of the six lasers is stacked in the fast axis as to preserve the fast axis beam quality, and is then individually collimated in the fast axis and slow axis. A single focusing objective is used to couple the emitters into a single fiber. The flexible packaging method scales to high power by accommodating multiple emitters, and is compatible with polarization multiplexing for packages with larger counts. Performance of a six-emitter package as coupled into a 105 µm fiber at 0.15 NA is shown in Figure 3(b) using standard chip and the REM-diode chips. We have already demonstrated higher fiber-coupled power of >75W in our preliminary assessment. These results closely match our model predictions. More work is underway to harness higher brightness that these diodes can afford using fully-optimized optics.

Figure 4(a) shows the model prediction of nLIGHT's *element*™ fiber-coupled package result for REM-diodes. A fully optimized REM-diode design along with corresponding optics is predicted to generate ~80W at 16A operation with ~47% efficiency. In a 2×6 emitter configuration our model prediction is shown in Figure 4(b). We expect >150W of output power with ~45% efficiency at 16A. The 6 and 12 chips are designed to couple light into a 105 µm fiber at 0.15 NA when using the REM-diodes. Figure 5 shows model prediction of an 18-chip package with REM-diode optimized for a 200 µm fiber at 0.108 NA. Our model predicts 250W of output power at 17A with 46% efficiency.

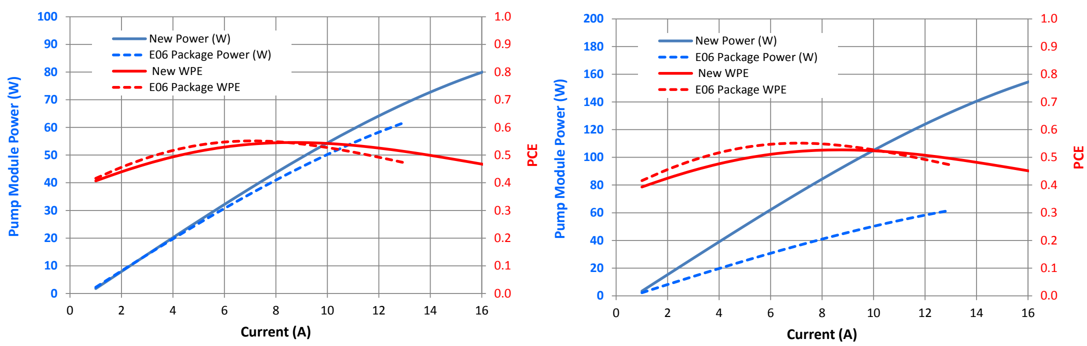


**Figure 5:** (a) The CW LIV and efficiency modeled performance for e-6 package using REM-diode Design-76. (b) e-12 modeled performance for the same design taking into account losses associated with polarization-multiplexing.

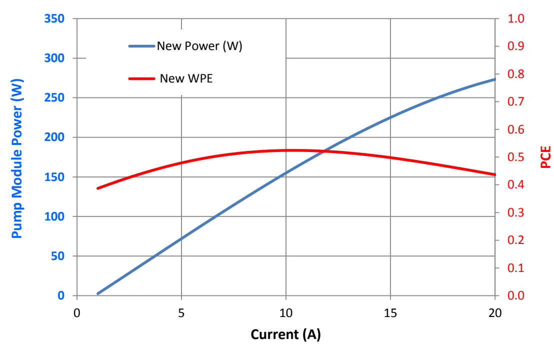


**Figure 6:** The CW LIV and efficiency modeled performance for an e-18 package with REM-diode chips and coupled into a 200 µm fiber at 0.108 NA. The larger fiber is required due to the 9 emitters stacked in the vertical direction. In this package polarization multiplexing is used to spatially overlap the emitters.

### 4. RELAIBILITY AND ENVIRONMENTAL QUALIFICATION OF FIBER-COPUPLED MODULES

Here we report on the reliability results for the broad area lasers & modules in the 790 nm to 980 nm range and preliminary reliability assessment of REM-diodes.

Life-test of 150 µm stripe and 5.0 mm cavity 808 nm diodes is shown in Figure 8. A total of 48 devices were tested at 12 A with a junction temperature of 58°C. In 3000 hours of life-test we have encountered only two failures but do not see any observable degradation amongst the other. The two failures observed are random failures and there is no sign of any COMD wear-out in the first 3000h. This life-test is still on-going.

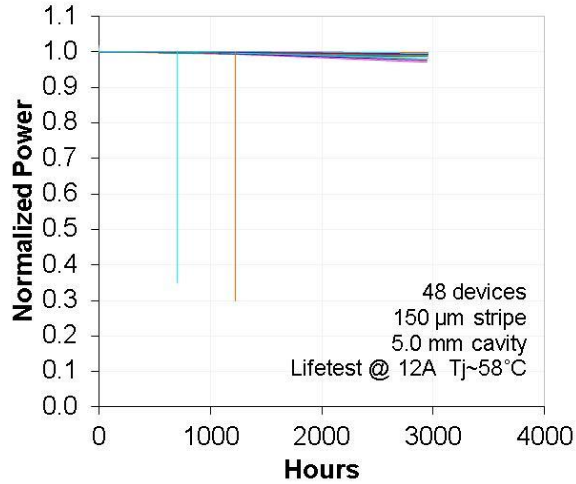


**Figure 8:** Life-test of 48 units of 808 nm 150 µm stripe and 5.0 mm cavity length broad area lasers operating at 12A and 58°C junction temperature.

An excellent method for verifying single-emitter reliability is to test devices connected in series in large-format packages. nLIGHT has developed Pearl™ modules that can provide as high as 400W from a 200 µm core fiber, or 500W from a 400 µm core fiber, with 56 or 72-emitters, respectively. nLIGHT has performed an extended life-test, as shown in Figure 9 with two units of 400W modules and two units of 500W modules. These units were life-tested at ~450W and ~550W respectively for > 15,000 hours, representing > 3.45 million device hours of operation. Of the 256 devices under test, only 1 chip failed within the first thousand hours, resulting in a measured FIT rate of <290. These results validate and corroborate the multi-cell life-test results that determined a FIT rate of ~ 500 for 3.8 mm cavity length devices rated at 10W. The multi-cell life-test and package level life-tests demonstrating FIT rates in the 500 range are further supported by a <<1% field failure rate for device failures since 2008. It is also well worth noting that a single device failure does not have an adverse impact on other devices that are connected in series. The package-level life-tests for the *element*™ fiber-coupled packages are underway, and will be reported next year.

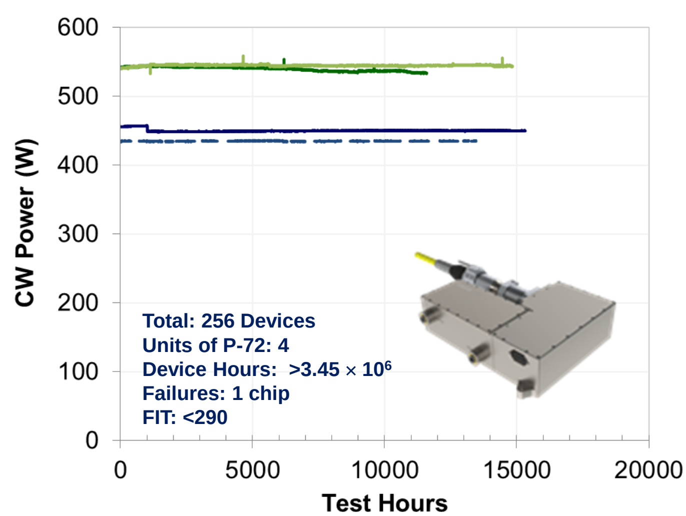


**Figure 9:** Module life-tests for two 400W P72's at ~450W and two 500W P72's life-tested at ~550W. There were 256 single emitter devices under test, a single failure in >3.45 million device-hours of operation, with a resulting measured FIT rate of <290.

A total of 236 9xx nm lasers of 75 µm wide stripe and 5.0 mm long cavity have been loaded for accelerated life-test at 18 A and junction temperature $T_j$~75 ˚C. The acceleration factor from the model based on power density, current density and temperature [11], is calculated to be ~13 times that of the typical operation at 12 W and junction temperature $T_j$~52 ˚C. The shortest device life-test time is 400h and the longest device life-test time is 6890h. Of the 236 devices, 9 random failures were observed out of $5.7\times10^6$ equivalent operational (12W) device hours. The exponential fitting [14] of the data suggest FIT~1620 and FIT<2800 with 90% confidence level for 12W operation shown in Figure 10. A comparison was also done to compare reliability of diode laser with 75 µm wide stripe and 5.0 mm long cavity to the reliability of diode laser with 95 µm wide stripe and 3.8mm mm long cavity (life-tested in a 2-year long multi-cell life-test). As shown in Figure 11, the device with 75 µm wide stripe and 5.0 mm long cavity show comparable or even slightly better reliability compared to the device with 95 µm wide stripe and 3.8mm mm long cavity, at the same operating power. FIT is <520 with 90% statistical confidence for the device with 75 µm wide stripe and 5.0 mm long cavity, running at 10W operation.

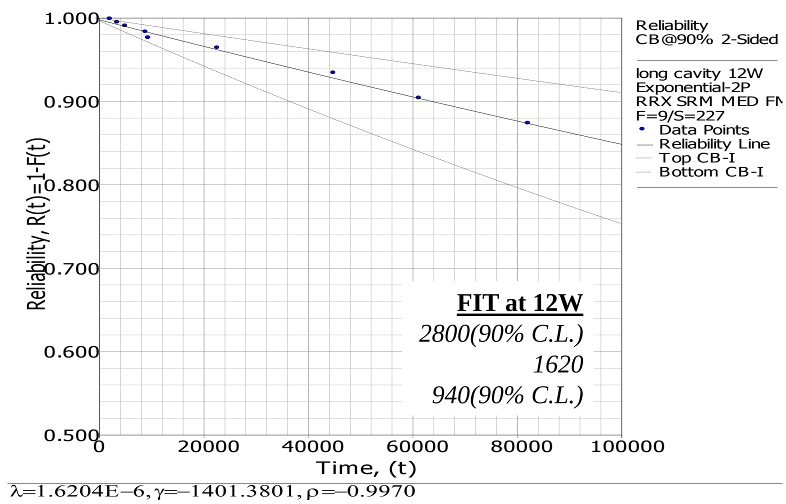


**Figure 10:** Reliability of 9xx nm devices of 75 µm stripe width and 5.0 mm cavity length life-tested at 18A $T_j$~75 ˚C and projected for 12W operation.

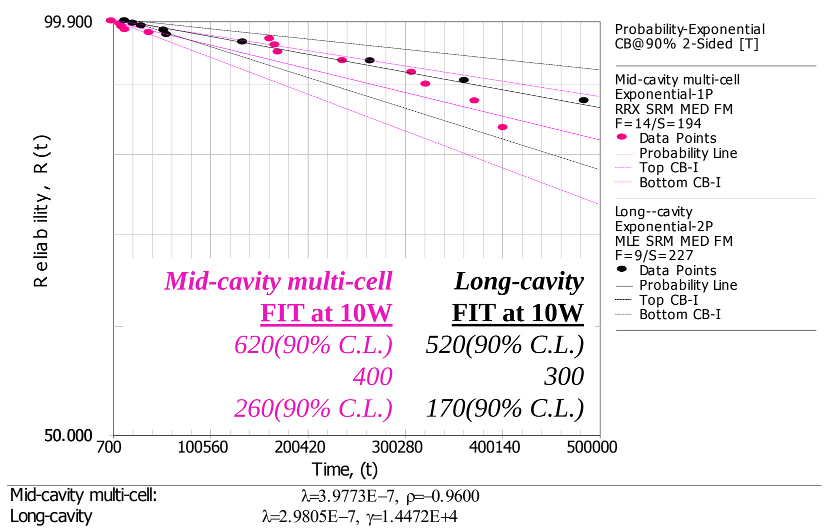


**Figure 11:** (Red dots) Reliability data for 3.8 mm cavity length multi-cell superimposed with (Black dots) 9xx nm devices of 75 µm stripe width and 5.0 mm cavity length life-tested at 18A $T_j$~75 ˚C and projected for 10W operation at the same junction temperature as the 3.8 mm cavity length devices.

We have started life-test of very high brightness REM-diodes at accelerated conditions.  In Figure 12 we show standard device and two of the REM-diode designs tested at 16A and 75°C junction temperature.  Two of the seven devices for standard design, under this highly accelerated conditions, show sudden failure.  One of the devices from REM-diode Design 72 shows one failure.  This design has the closest area to the standard device.  REM-diode Design 74 is still running after 2500 hours without any failures.  These initial results show that the REM-diodes do not display any deleterious behavior.  We will be performing a full multi-cell reliability assessment and publish our results in the future.

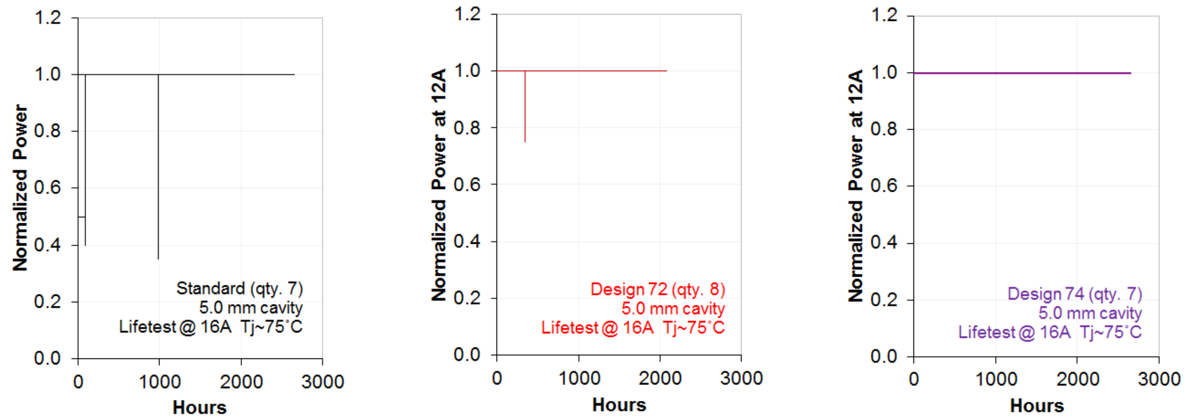


**Figure 12:** (a) Accelerated life-test of standard 9xx nm 75 µm × 5 mm laser diode at 16A and junction temperature of 75°C (b) REM-diode Design 72 and (c) REM-diode Design 74 under the same conditions.

As part of the package qualification, nLIGHT performs package-level environmental stress tests to verify and validate the package design. These tests include a low temperature (-20 ˚C) soak test, a high temperature soak test (80 ˚C), temperature cycling (-20 to 80 ˚C), mechanical shock tests on 3 axes, and mechanical vibration tests on three axes. The LIV and operating spectrum were used to verify the qualification and the data has been previously published [13].  A list of module-level qualifications completed is shown in Table 1.  nLight offers best in class reliability; our *element*$^{TM}$ series of fiber laser pumps have all undergone extensive validation and qualification testing in eight areas: Shock, Vibration, Non-Operational Temperature Cycling (NOTC), Low Temperature Storage, High Temperature Storage, Elevated Temperature & Humidity Storage, Lifetest, and finally On-Off Life-test.  Portions of the nLight *element*$^{TM}$ qualification test program were taken from GR486.)

| Test | Description | Group | Pass/Fail |
|---|---|---|---|
| B.R1 | Temperature cycle (-20 to +80 ºC 3 ºC/min, 10 min dwells, 25 cycles | 1 | Pass |
| B.R2 | Low Temperature Soak (-20 ºC for 150 hours) | 2 | Pass |
| B.R3 | High Temperature Soak (80 ºC for 150 hours) | 3 | Pass |
| B.R4 | Mechanical Vibration (5 g, 3 axes, 20 Hz – 2 kHz sweeps) | 4 | Pass |
| B.R5 | Mechanical Shock (50 g [100 g, 6 ms, 6 directions, 3 axes, 3 drops each) | 4 | Pass |
| B.R6 | Lifetest (1000 hour ) | 5 | Pass |
| B.R7 | On-Off Lifetest (5 min on, 5 min off for 100 hours) | 6 | Pass |

- Power, ≤ 10% change (≤ 20% change for lifetests)
- Wavelength Centroid, ≤ 1 nm change
- FWHM, ≤ 1 nm change
- Wall Plug Efficiency, ≤ 10% change

**Table 1:** nLight Reliability Qualification Plan for the *element*$^{TM}$ series of fiber laser pumps.

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 is ongoing, the accumulated accelerated life-test hours provide confidence in the overall reliability of these devices. Table 2 is a summary of the performance and the rated power of these next-generation high power/brightness devices with 5.0 mm cavity length.

| Chip Key Parameters | 75 µm 5.0 mm Chip | REM 5.0 mm Chip | 150 µm 5.0 mm Chip | 150 µm 3.8 mm Chip | 150 µm 5.0 mm Chip | 350 µm 3.8 mm Chip |
|---|---|---|---|---|---|---|
| Wavelength | 910-990 nm | | | 790-815 nm | | |
| Max Rated Power | 12W | 14W (Under Dev.) | 18W | 6W | 8W (under Dev.) | 15W |
| Peak efficiency | 65% | 65% | 65% | 60% | 63% | 63% |
| **Module Key Parameters** | **E06** | **E18** | **E18** | **E03** | **E03** | **E03** |
| Fiber | 105 µm | 105 µm | 200 µm | 200 µm | 200 µm | 400 µm |
| Max Rated Power | 60W | 70W (Under Dev.) | 200W | 15W | 18W (Under Dev.) | 35W |
| NA | 0.15 | 0.15 | 0.22 | 0.22 | 0.22 | 0.22 |

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

## 4. CONCLUSIONS

In summary, we present recent progress in the development of high power/brightness single emitter laser diodes and fiber coupled multi-emitter laser diode pump modules. The current products are based on a 75 µm emitter stripe width device, with rated output power of approximately 12A. The reduction of emitter stripe width from the traditional 95 µm to 75 µm increases the power that can be coupled into a 105 µm fiber at 0.13 NA by approximately 30%. By increasing the emitter width to 150 µm, the useable output power is increased to 18W, and the light can be efficiently coupled into a 200 µm fiber at 0.13 NA. We have developed a new high brightness laser diode chip with fewer modes, hence, termed Reduced-Mode-diodes (REM-diodes). The best design evaluated thus far shows a peak brightness of ~3.6 W/mm-mrad at 15W; whereas, standard device has a peak brightness of ~3 W/mm-mrad near 12W output power. Using these chips we demonstrated >75W from 105 µm fiber, 0.15 NA at 15A in a 1×6 *element*™ package. Our model shows that these chips are capable of producing *element*™ packages with output power of more than 150W from 105 µm fiber, 0.15 NA at 16A and 250W from 200 µm fiber, 0.108 NA at 17A. Using REM-diodes, the package power and brightness can be simply optimized for $/W or fiber coupled brilliance. These packages are demonstrated to be robust even under strenuous package environmental qualification tests.

## REFERENCES


[1] E. C. Sousa, I. M. Raniere, S. L. Baldochi, and N. U. Wetter, "Compact diode-side-pumped Nd:YLF laser with high beam quality," AIP Conf. Proc. 992, 426 (2008).

[2] Platonov, N. S., Gapontsev, D. V., Gapontsev, V. P., Shumilin, V., "135W CW Fiber Laser With Perfect Single Mode Output," Proc. Lasers and Electro-Optics, Post-deadline Paper, CPDC3 (2002).

[3] Limpert, J., Liem, A., Zellmer, H. and Tünnermann, A., "500W continuous-wave fiber laser with excellent beam quality," Electronics Letters 39, 645 (2003).

[4] Liu, C –H., Galvanauskas, A., Ehlers, B., Doerfel, F., Heinemann, S., Carter, A., Tankala, K. and Farroni, J., "810W single transverse mode Yb-doped fiber laser," Proc. Advanced Solid-State Photonics, Post-deadline Paper, PDP17 (2004).

[5] Jeong, Y., Sahu, J., Payne, D. and Nilsson, J., "Ytterbium-doped large-core fiber laser with 1.36 kW continuous wave output power," Optics Express 12, 6088 (2004).

[6] Gapontsev, D., "6kW CW single mode Ytterbium fiber laser in all-fiber format," Proc. Solid State and Diode LaserTechnology Review, 1 (2008).

[7] S. R. Karlsen, R. K. Price; M. Reynolds, A. Brown, R. Mehl, S. Pattern, R. J. Martinsen, "100-W, 105-μm, 0.15 NA Fiber Coupled Laser Diode Module," Proc. of SPIE 7198, 71980T (2009).

[8] K. Price, S. Karlsen, P. Leisher, R. Martinsen, "High Brightness Fiber Coupled Pump Laser Development," Proc. of SPIE 7583, 758308 (2010).

[9] Ling Bao, Paul Leisher, Jun Wang, Mark Devito, Dapeng Xu, Mike Grimshaw, Weimin Dong, Hua Huang, Shiguo Zhang, Damian Wise, Rob Martinsen, and Jim Haden "High Reliability and High Performance of 9xx-nm Single Emitter Laser Diodes," Proceedings of SPIE 7918, 7918 (2011).

[10] L. Bao, M. Devito, M. Grimshaw, P. Leisher, H. Zhou, W. Dong, X. Guan, S. Zhang, R. Martinsen, and J. Haden, "High Performance Diode Lasers Emitting at 780-820 nm," Proc. of SPIE 8241, 824109 (2012).

[11] L. Bao, J. Bai, K. Price, M. Devito, M. Grimshaw, W. Dong, X. Guan, S. Zhang, H. Zhou, K. Bruce, D. Dawson, M. Kanskar, R. Martinsen, J. Haden, "Reliability of High Power/Brightness Diode Lasers Emitting from 790 nm to 980 nm," Proc. Of SPIE 8605, 860523 (2013).

[12] H. Koenig, G. Groenninger, C. Lauer, A. Hammer, J. Maric, U. Strauss, H. Kissel, M. Haag, J. Bissenbach, "Brilliant low fill factor diode laser bars at 9xx nm for fiber coupling," Proc. Of SPIE vol. 7198, 719803 (2009).

[13] Kirk Price, Marty Hemenway, Ling Bao, John Bai, Kylan Hoener, Kevin Shea, David Dawson, Manoj Kanskar, "High Brightness Fiber Coupled Pump Modules Optimized for Optical Efficiency and Power," Proc. Of SPIE 8605, 860523 (2013).