Continued Advances in High-Brightness Fiber-Coupled Laser Modules for Efficient Pumping of Fiber and Solid-State Lasers

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ABSTRACT

Both the fiber laser and diode-pumped solid-state laser market continue to drive advances in pump diode module brightness. We report on the continued progress by nLIGHT to develop and deliver the highest brightness diode-laser pumps using single-emitter technology. Continued advances in multimode laser diode technology [13] and fiber-coupling techniques have enabled higher emitter counts in the element® packages, enabling us to demonstrate 305 W into 105 µm – 0.16 NA. This brightness improvement is achieved by leveraging our prior-reported package re-optimization, allowing an increase in the emitter count from two rows of nine emitters to two rows of twelve emitters. Leveraging the two rows of twelve emitter architecture, product development has commenced on a 400 W into 200 µm – 0.16 NA package. Additionally, the advances in pump technology intended for CW Yb-doped fiber laser pumping has been leveraged to develop the highest brightness 793 nm pump modules for 2 µm Thulium fiber laser pumping, generating 150 W into 200 µm – 0.18 NA and 100 W into 105 µm – 0.15 NA. Lastly, renewed interest in direct diode materials processing led us to experiment with wavelength multiplexing our existing state of the art 200 W, 105 µm – 0.15 NA package into a combined output of 395 W into 105 µm – 0.16 NA.

Key words: Diode reliability, fiber-coupled diode laser, pump diodes, diode lifetime, life-test, brightness, fiber laser, Thulium

1. INTRODUCTION

Last year [12], nLIGHT reported on our established Brightness trend over the last decade for non-wavelength multiplexed diode modules used for pumping fiber lasers. We are pleased to report continued progress in this arena, as indicated in Figure 1 below, with the addition of the 2018 data point with a demonstrated brightness of ~4.6 W/(mm-mR)^2 and a forward looking theoretical limit of ~5 W/(mm-mR)^2 , based upon a 16 W laser diode [13] with a slow-axis BPP of 5 mm-mr.

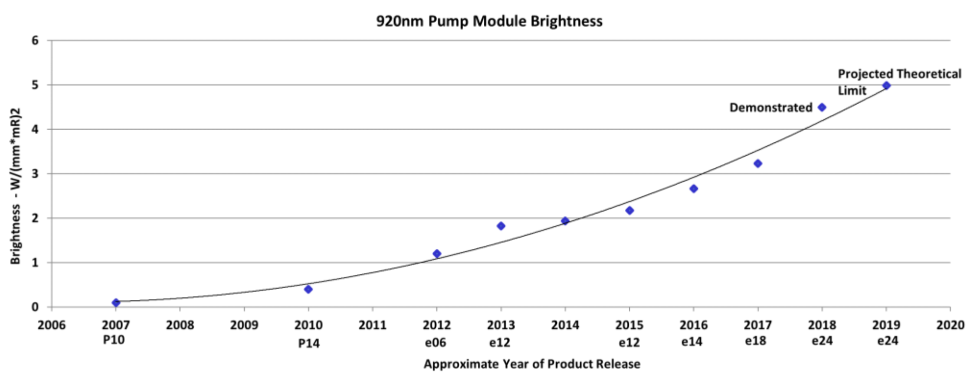

Figure 1. nLIGHT 920 nm pump module brightness trend.

In our prior paper [12] we predicted the maximum number of emitters one can stack in the fast axis, while also minimizing optical losses, for a given BPP can be displayed as,

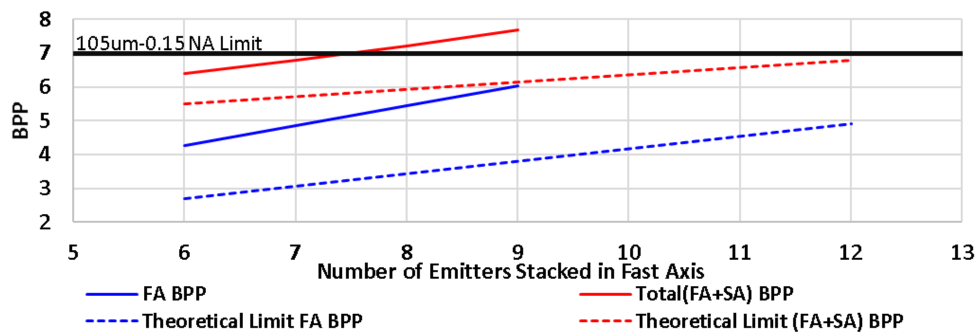

Figure 2. nLIGHT predicted BPP as a function of emitters.

where the solid lines represent the original element® opto-mechanical design, and the dashed lines represent a theoretical limit, assuming a fast axis BPP of 0.36. The equations for modeling multiple emitters coupled into a given fiber diameter and NA are concisely stated by Yu, et al [10], and will not be repeated here, but are useful for understanding this analysis. Using results for device BPP reported in [12] we plotted the excitation NA for 105 µm fiber as a function of the number of emitters in Figure 3. In 2017 we communicated how the original element® optical design followed the trend plotted with the red line in Figure 3, and limited the total number of fast axis emitters that could be used to launch into 105 µm – 0.15 NA to seven. The re-optimization efforts for the 2×9 diode configuration released in 2017 established a new (blue) trend line, enabling a 9-emitter stack to be coupled into 0.15 NA. A question remained: By using a new laser diode architecture [13] with improved brightness, could we validate the trend displayed with the green trend line, which represented the theoretical limit?

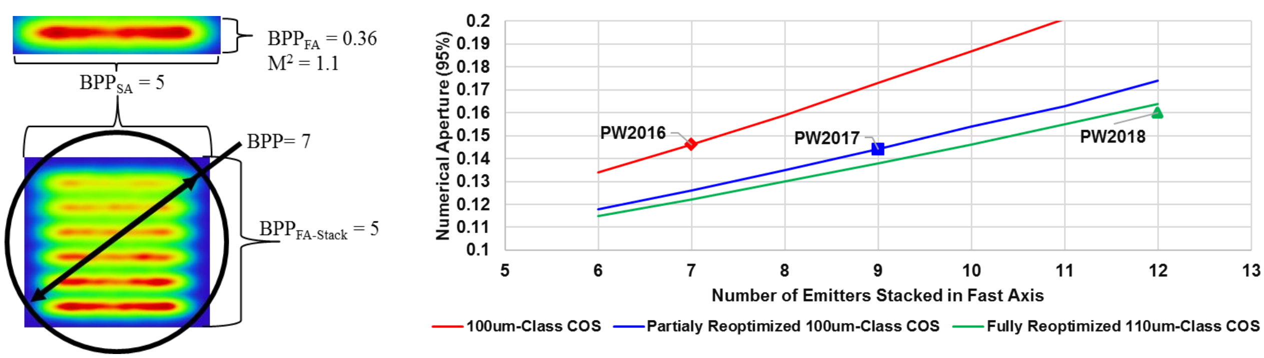

Figure 3. nLIGHT predicted diode module NA as a function of emitters and design architecture.

The details presented in the following paragraphs will summarize the results that have been realized by leveraging the analysis outlined above.

2. 920 & 976 MODULE RESULTS

To maintain the trend predicted in Figure 3, we have been experimenting with a 2×12 diode configuration, where two banks of 12 emitters with the same wavelength are polarization multiplexed, with the multiple variables fully optimized to efficiently couple into 105 µm fiber with a 0.15 excitation NA. Utilizing our latest prototype 100 µm-class devices, we are immensely excited to report that we were able to couple 24-emitters into 105 µm fiber, measuring 285 W at 15 A and 0.15 NA and a maximum power of 305W at 17 A coupled into 0.157 NA, resulting in a peak brightness of 4.63 W/(mm*mR)^2 occurring at 14 A, which we believe to believe to be a new record for single wavelength power and brightness into 105 µm fiber. The brightness was still 4.49 W/(mm-mR)^2 at 17 A. We are unaware of any other efforts that have been successful in coupling more than 18 high-power multimode laser diodes, of the same wavelength, into 105 µm – 0.15 NA.

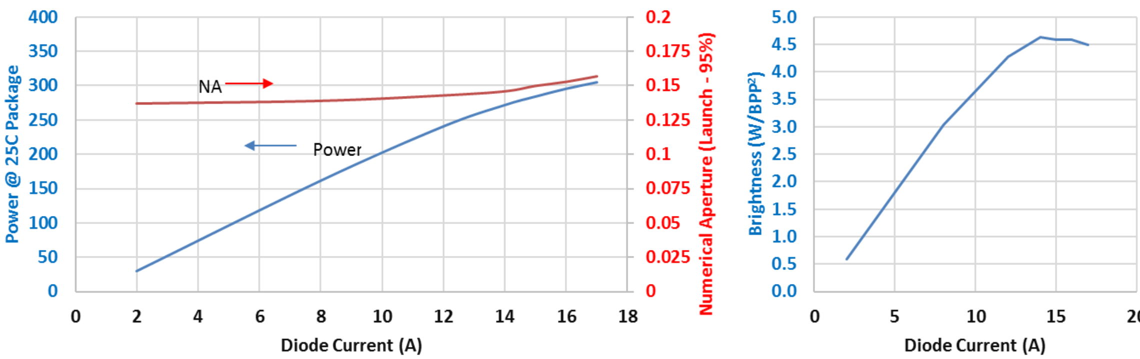

Figure 4. nLIGHT measured performance for a 2×12 polarization multiplexed diode module at 920 nm, coupled into 105 µm fiber.

The 2×12 package demonstrated above had a measured fiber coupling efficiency of 90%, which is about 5% lower than typical element® designs. This reduction in fiber coupling efficiency was a conscious tradeoff to reduce the NA slightly, so that it remained below 0.16 NA along the entire current range. Additionally, the newest laser diodes, after submount and package bonding, averaged 95 % TE polarization purity over the entire current range, with no degradation in polarization at higher currents. Importantly, these results validate our prior predictions that it is possible to couple a 12-emitter, fast axis stack into 105 µm – 0.15 NA [12].

While some applications drive the need for ever-higher brightness, other simply demand higher power. To this end, broad area laser diodes (BALs) can be increased in their slow axis width to increase power, at the expense of brightness [13]. The tradeoffs between power and slow axis brightness is demonstrated below in Figure 5, where we compare the LI and BPP of two laser diodes optimized for the 2×12 configuration, one for coupling into 105 µm – 0.15 NA (dashed lines), vs a second laser diode with a wider waveguide optimized for 200 µm fiber – 0.16 NA (solid lines).

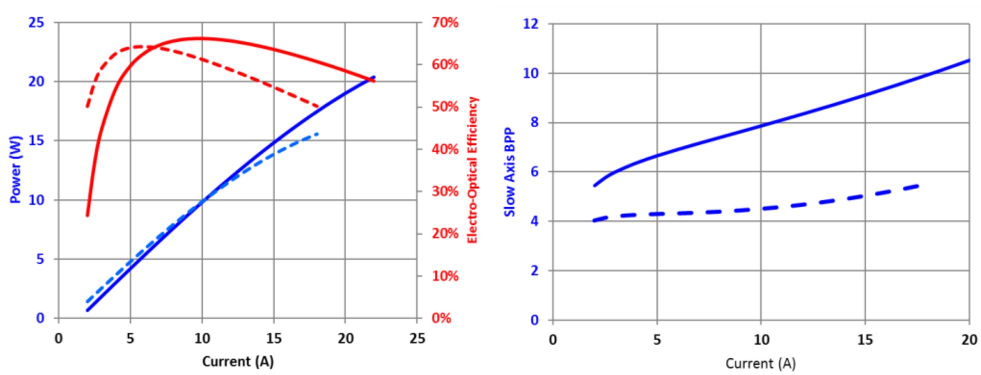

Figure 5. nLIGHT predicted performance (power and efficiency – left, BPP – right) for two different chip on submount laser diodes, with the device optimized for 200 µm fiber depicted with solid lines, and the device optimized for 105 µm fiber depicted with dashed lines.

Figure 5 immediately communicates three things, first the wider slow axis device used for 200 µm fiber based diode modules designs can operate at a much higher current level before the LI curve begins to roll over, second the device efficiency degrades much more slowly at higher current for the larger device, and finally this performance comes at a cost of a slow axis BPP which is nearly 2x higher than that of the device optimized for 105 µm fiber. Of course, such an exercise is useless to a product unless the devices are reliable. For this, we can predict based upon the Arrhenius equation,

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

the relative reliability of the two devices with respect to each other. In this exercise the variables in equation (1) are m=n=2, an activation energy (E_a) of 0.45 eV was used, the junction temperature (T_j) was calculated for each device as a function of current, P is the power density, I is the current density, and k_B is Boltzmann's constant.

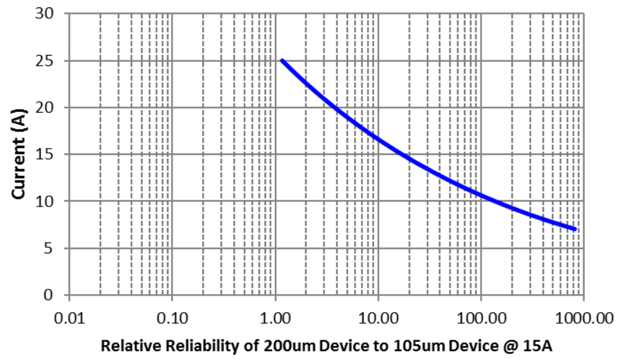

Figure 6. nLIGHT predicted *relative* reliability for COS optimized for 200 µm fiber module vs the device optimized for 105 µm fiber.

The chart presented in Figure 6 should be interpreted as follows: At 25 A, the 200 µm laser diode has approximately 1:1, or the same reliability as our laser diode optimized for 105 µm fiber operated at 15 A, when operated under the same environmental conditions. This implies that establishing a beginning of life operating current of 20 A for the 200 µm device is a reasonable initial prediction. Lifetests are underway to validate the reliability of the COS, although the predictions used in this analysis have been validated with prior lifetest results for other laser diode designs.

The benefit of using lower brightness but higher power diodes, and coupling them into 200 µm fiber results in a pump module with very high-power levels, while using a minimum number of emitters, all within a package that is small, lightweight, and efficient. This realization drove nLIGHT to develop a new pump module, with 200 µm fiber, and the corresponding laser diodes optimized to efficiently couple into 200 µm – 0.16 NA, with a beginning-of-life operating current of 20A. Theoretically, with 2 banks of 12 polarization multiplexed emitters, the predicted result is 395 W output with a 50 % electrical to optical conversion efficiency when the package is operated at 25 °C. Initial prototype units average 394 W with a 50 % electro-optical package efficiency (Figure 7) and a measured NA of 0.163 at 20 A, which very closely matches our predictions generated by our custom modeling software and Zemax. Importantly, the new 2×12 package is compact, having dimensions of approximately 130 x 60 x 20 mm^3.

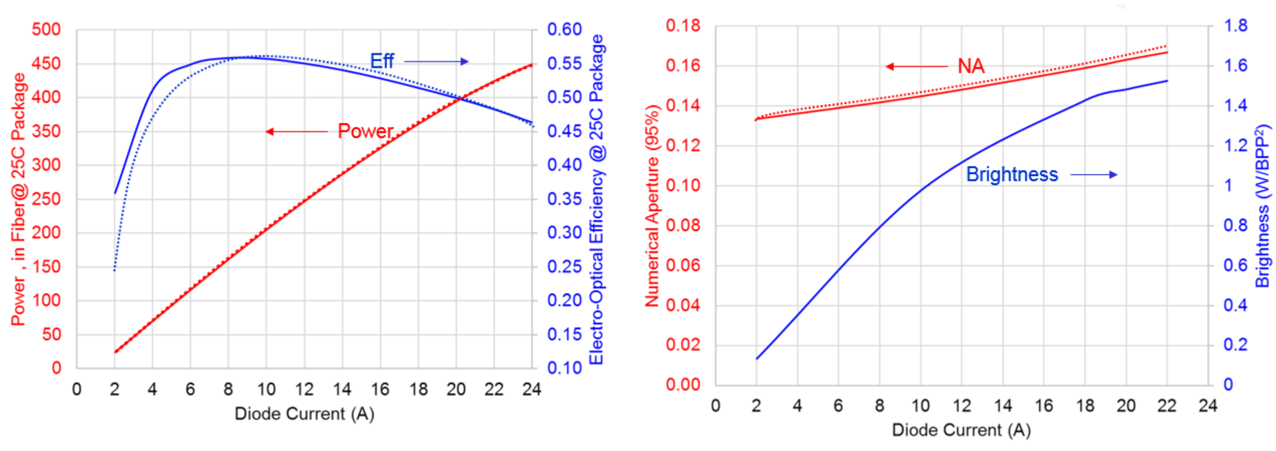

Figure 7. nLIGHT measured average performance for 14, 2×12 diode modules at 976nm, coupled into 200 µm fiber. Theoretical results are indicated with dashed lines, with measured results plotted with solid lines.

Regarding the overall robustness of the new 2×12 package, the conductively cooled, proximal fiber assembly is measuring approximately 12 °C hotter that of the package baseplate. The small elevation in fiber temperature confirms a very high, measured fiber coupling efficiency of 95 %, along with a COS polarization which is steady at 95% TE polarization purity as measured from 2 A to 24 A. Overall, these results indicate the package design is operating very efficiently, indicating a reliable package. Additionally, two of these Alpha modules have successfully undergone environmental testing for shock (5G and 10G), vibration (50G and 100G), and temperature cycling (25 cycles -20 to +80 °C and 75 cycles -30 to +80 °C), with a measured change in power of less than 3 %, and no change in wavelength or NA. Given that thermopile measurement error is on the order of +/- 2 %, the measured changes are on the order of measurement error.

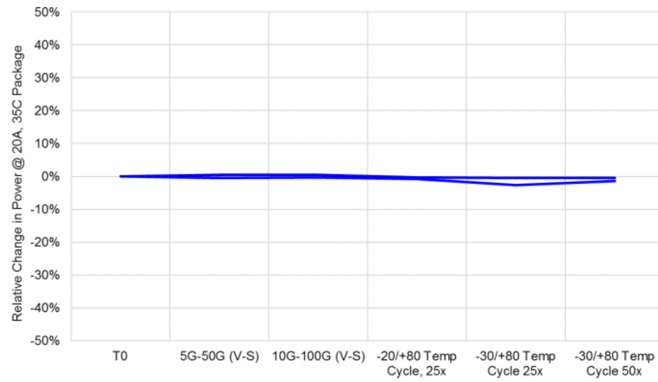

Figure 8. nLIGHT measured environmental performance for two, 2x12 diode modules at 976nm, coupled into 200 µm fiber.

3. WAVELENGTH MULTIPLEXING RESULTS

In 2015 the nLIGHT element® team wavelength multiplexed two element® 2×6 modules, as an internal study, to see how efficiently we could wavelength multiplex our element® pumps. That original experiment used two of our 130 W packages operating at 14 A, one at 920 nm and one at 976 nm, to achieve 268 W of wavelength multiplexed power into a measured 0.151 NA with 105 µm fiber, and with 94 % fiber coupling efficiency. However, most important to us, was that our measurements of the wavelength multiplexed power compared to the individual package power were identical, indicating the losses incurred by our dichroic was within the measurement noise of the thermopile used for the experiment. A schematic representation of our experimental layout is illustrated below.

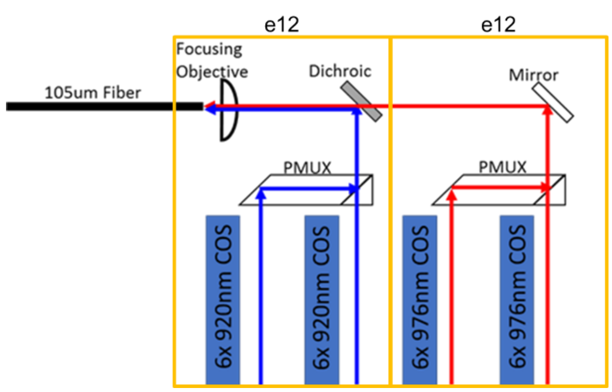

Figure 9. nLIGHT layout for two 2×6 diode modules (920nm + 976nm) wavelength multiplexed together into a single 105 µm fiber.

The importance of this test was to validate the efficiency of the dichroic used to wavelength combine the beams, and show that we could do so with minimal degradation in the launch NA. Additionally, the prototype was placed on a long-term life test to gain a preliminary understanding of both the stability of the dichroic over time, and the robustness of our 105 µm fiber assembly at this elevated power. The module was operated for 6400 hours continuously at 40 °C before the test was stopped, with only a 2 % degradation in output power from the module. Analysis conducted on the module after removal from the life test was inconclusive on the mechanism responsible for the 2% degradation over the 6400-hour period; it is possible that due to the very small change, accurately measuring individual changes in optical component transmission was within our measurement noise.

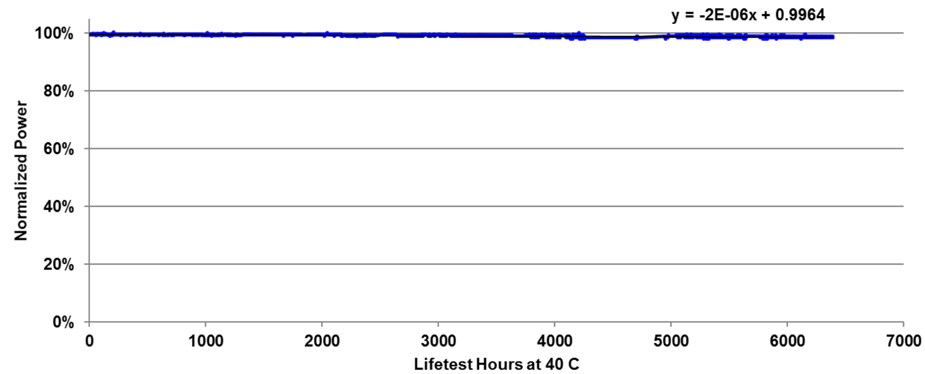

Figure 10. nLIGHT life test results for a prototype wavelength multiplexed module outputting 268 W into 105 μm fiber.

With the release of the new element® 2×9 modules in 2017, outputting nearly 200 W into 105 μm – 0.15 NA fiber, we decided to repeat our 2015 experiment with the new 2×9 diode module, once again with one module at 920 nm and one at 976 nm. Surprisingly, the measured results showed only a 0.4% loss through our wavelength multiplexing optic at 14A, which resulted in a total power of 395 W (Figure 11). Of note however, the proximal fiber assembly temperature in increased to a rather warm 76 °C, which in turn was attributed to poor FAC collimation of the 976 nm COS, resulting in a very low 83 % fiber coupling efficiency for the 976 nm diodes. If the 976 nm FAC collimation had been correct, it is estimated the overall power would have increased by 20 W at 14 A, for a total power of 415 W.

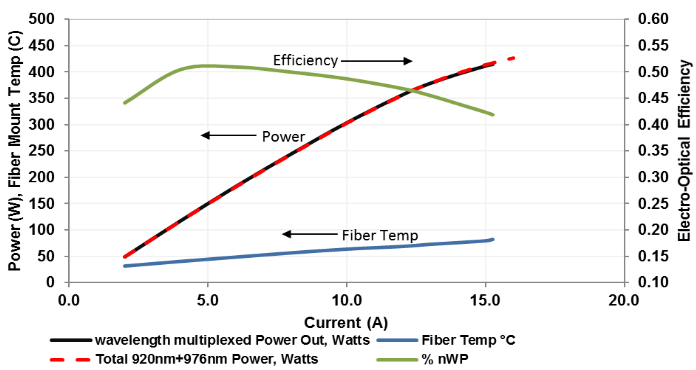

Figure 11. nLIGHT measured performance for two 2×9 diode modules (920nm + 976nm) wavelength multiplexed together into a single 105 μm fiber.

Even with the lower than expected fiber coupling efficiency at 976 nm, overall the results communicated above provide data supporting that our dichroic design remained very low loss, even at nearly 400 W of power

4. 793 / 808 MODULE RESULTS

793 nm diodes are critical for efficient pumping of Thulium fiber lasers with emission in the 2 μm range; utilizing the design changes previously reported for our 920 nm devices, our existing element® e18 was updated with a revised 793 nm diode epitaxy to manage polarization purity, coupled with two new COS configurations reoptimized for efficient coupling into both 200 μm and 105 μm fiber. The revised 793 nm package design is based upon our NA compression technology outlined in our prior paper [12]. Pilot production, 200 μm fiber modules, are shipping to customers with an average power of 132 W at the beginning-of-life current of 10 A, and a maximum power of 161 W at 12 A (Figure 12). The 18-emitters are coupling into the 200 μm fiber with a measured average 97 % coupling efficiency, and a launch NA of 0.17. Additionally, achieving high polarization purity at 793 nm is a challenge, although the new epitaxy is exhibiting a stable TM polarization purity of 92 % from 2 A to 12 A. To our knowledge, these are the highest power and highest brightness 793 nm diode pump modules in production.

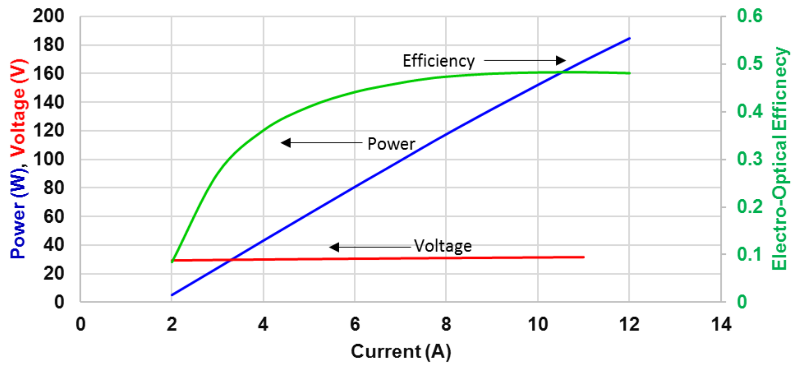

Figure 12. nLIGHT measured average performance for thirty, 2×9 diode modules coupled into 200 µm fiber with a 0.17 excitation NA.

In addition, the Thulium fiber laser market has shown renewed interest in 105 µm fiber pumps. Therefore, development has commenced upon a similar design to the one outlined above, but utilizing a COS with sufficient brightness to efficiently couple into 105 µm fiber with an excitation NA of 0.15. The higher brightness 793 nm BAL has a reliability rated beginning-of-life current of 6.5 A, resulting in an estimated 18-emitter package output power of 95 W, with an extremely linear LI to 14A. In Figure 11, we provide the measured COS power, along with the modeled 18-emitter package power and efficiency, when coupled into 105 µm fiber.

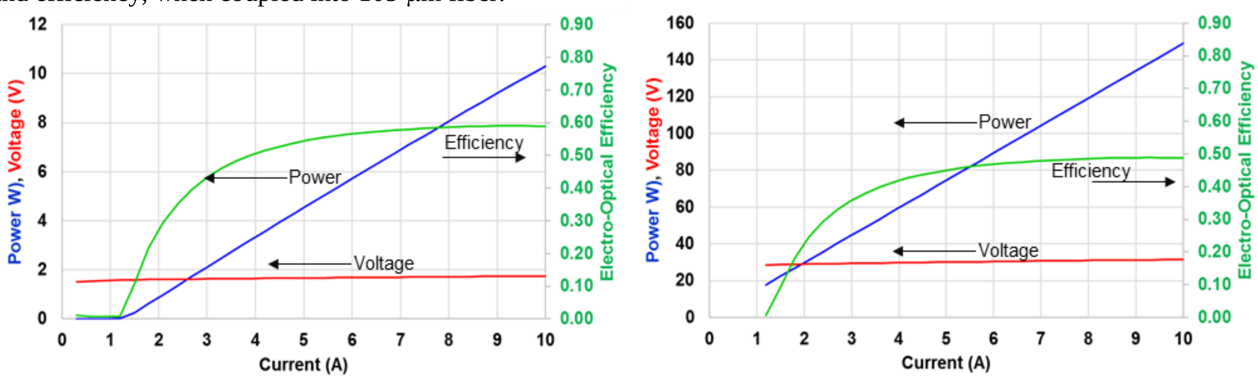

Figure 13. nLIGHT measured COS performance for high-brightness 793 nm device (left), and modeled 2×9 diode module performance (right).

5. E18 PACKAGE LIFESTEST UPDATE

Last year [12] we reported on the extended life test of eight element® e18 modules operating at 200 W launched into 105 µm fiber. The same life test was continued until June 2017, with the modules accumulating 48,637 combined hours, with no package induced failures. The 48,637 hours, after accounting for the total number of COS on the life test and the slightly accelerated conditions (Eq. 1) by operating the packages at 40˚C, scales to an equivalent of 1.29 million device hours. Over this period, 3 COS failed, resulting in a 2.08% failure rate, and a FIT value of 2331. Most importantly three element® e18 modules operated continuously for over one year, without a package induced failure or measurable degradation, and no modules were removed ore replaced from the test due to failures.

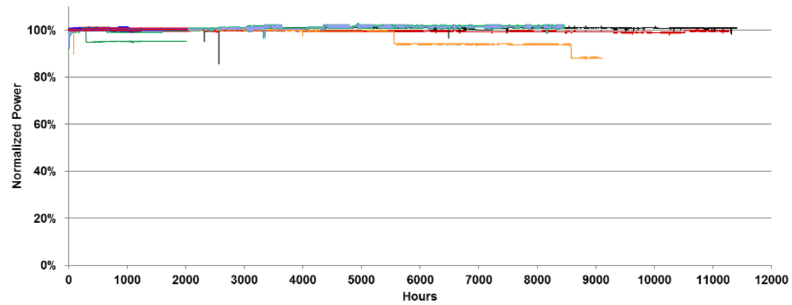

Figure 14. Normalized power for eight 200 W element® e18s with 105 μm-0.22 NA fiber, with a 100 μm class COS, and one 225 W element® e18 with 105 μm-0.22 NA fiber, with next gen 110 μm class COS, at 40 ˚C package temperature.

6. CONCLUDING REMARKS

nLIGHT continues to drive innovation in multi-emitter diode modules, as demonstrated by successfully coupling 24-emitters into 105 μm fiber with an excitation NA of 0.15 for 305 W output, and wavelength multiplexing two 18-emitter modules together to couple into 105 μm fiber with an output of 395 W, and through the productization of a 400 W class 24-emitter module coupled into 200 μm fiber. Additionally, the demonstrated results of our low-loss wavelength multiplexing, stable long-term life test, and aggressive environmental testing attest to our attention to DFx principles for robust and reliable products.

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