Improvement in Reduced-mode (REM) Diodes Enable 315 W from 105 µm 0.15 NA Fiber-coupled Modules

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ABSTRACT

High-power, high-brightness diode lasers have been pursued for many applications including fiber laser pumping, materials processing, solid-state laser pumping, and consumer electronics manufacturing. In particular, ~915 nm – and ~976 nm diodes are of interest as diode pumps for the kilowatt CW fiber lasers. As a result, there have been many technical thrusts for driving the diode lasers to have both high power and high brightness to achieve high-performance and reduced manufacturing costs. This paper presents our continued progress in the development of high brightness fiber-coupled product platform, nLIGHT *element*®. In the past decade, the power coupled into a single 105 µm and 0.15 NA fiber has increased by over a factor of ten through improved diode laser brightness and the development of techniques for efficiently coupling multiple emitters. In this paper, we demonstrate further brightness improvement and power-scaling enabled by both the rise in chip brightness/power and the increase in number of chips coupled into a given numerical aperture. We report a new chip technology using x-REM design with brightness as high as 4.3 W/mm-mrad at a BPP of 3 mm-mrad. We also report record 315 W output from a 2×12 nLIGHT *element* with 105 µm diameter fiber using x-REM diodes and these diodes will allow next generation of fiber-coupled product capable of 250W output power from 105 µm/0.15 NA beam at 915 nm.

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

1. INTRODUCTION

There is increasing demand for 915 nm - 976 nm diodes as diode pumps for the kilowatt CW fiber lasers [1-2]. In the past decade, the amount of power coupled into a single 105 µm and 0.15 NA fiber has increased by an order of magnitude through improved diode laser brightness and the development of techniques for efficiently coupling multiple single emitters into a single fiber [3-7]. Over the past several years, nLIGHT has continuously improved output power and brightness of broad area laser diode chips by optimizing the cavity length and emitter width, primarily enabled by lower-loss epitaxial structures. Although, higher power operation is possible from these low-loss devices, useful brightness scaling has been limited to 12W output power per BAL-chip for coupling into a 105 µm/0.15 NA fiber. Beyond this power, a rapid increase in slow-axis divergence, referred to as “slow-axis blooming”, limits useful fiber-coupled power [3-4]. Historically, techniques such as increasing the cavity length, reducing the lateral index contrast, and tailoring the thermal lens induced lateral index profile have been used to mitigate the slow-axis divergence blooming issue. These past efforts produced modest improvement but no substantial performance improvement has resulted with useful brightness enhancement until the introduction of reduced-mode (REM) diode technology [6]. We have further improved REM diode technology to take advantage of multiple higher order mode suppression techniques. We refer to this improved REM diode technology as x-REM technology.

2. NEW REDUCED MODE DIODES (x-REM-DIODES)

nLIGHT introduced a new class of broad area lasers called REM-diodes [6-7] a couple of years ago. These devices allowed further scaling-up in slow-axis brightness. To achieve the designs with a maximum brightness at a given BPP, REM-diodes at wavelengths of 885nm, 915 nm and 976 nm with a range of emitter widths were studied. At all these wavelengths, the epitaxial structures were based on low-loss design with optimized doping profile to balance the effects of intrinsic and Joule heating losses. These designs also comprised large optical cavity (LOC) which reduces facet

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optical irradiance in the fast-axis while achieving high electrical-to-optical power-conversion efficiency (PCE). The cleaved bars were processed with nLIGHT's extended lifetime (*n*XLT) facet passivation.

nLIGHT's REM-diode design allows suppression of higher order modes which enables use of wider emitters to scale up in power without compromising the slow-axis beam-parameter product (BPP); thus, resulting in inherently higher brightness devices. We achieved this by reducing the thermal lensing effect as well as reducing the allowed number of modes in the slow-axis direction. nLIGHT fabricated REM-diodes with a range of emitter widths and compared them to standard broad area lasers. Invariably, the REM-diodes display lower slow-axis divergence. This allows us to operate REM-diodes with larger emission widths resulting in larger pumped areas. Consequently, for the same beam-parameter-product (BPP), the thermal footprint of these devices is larger making the thermal and the series resistances lower. The rollover power is higher for these devices and the efficiency does not drop off as quickly as the standard BALs when operating beyond the peak efficiency. As a result, the REM-diodes are more efficient at the same operating powers. Figure 1 (Left) shows maximum slow-axis brightness as a function of BPP for a wide range of REM diode designs explored near 9xx nm wavelength. The circular symbols denote the maximum slow-axis brightness as a function of BPP for 5 mm long REM-diodes of various designs with BPP in the range of 3 to 20 mm-mrad. The colored circular dots are average values for the data for a set of various REM-diode designs explored. The dotted lines show the boundary of the maximum slow-axis brightness that is achievable at any chosen BPP for a given REM architecture. REM architectures allows a continuously variable slow-axis brightness (from the value achievable with a regular BAL to the maximum value shown by the dotted line) for a given BPP. Most of the REM-diode designs show higher brightness compared to BALs for a chosen BPP value. Our development effort is to identify the designs that present maximum brightness at a given BPP. The dotted line in Figure 1 (Left) shows the maximum brightness possible at a given BPP from REM-diodes. It shows that in absolute terms, REM-diodes have improved brightness more than when increasing the cavity length from 3.8 mm to 5 mm for a fixed BPP. To date, we have measured REM-diodes with brightness as high as 4.3 W/mm-mrad at a BPP of 3 mm-mrad.

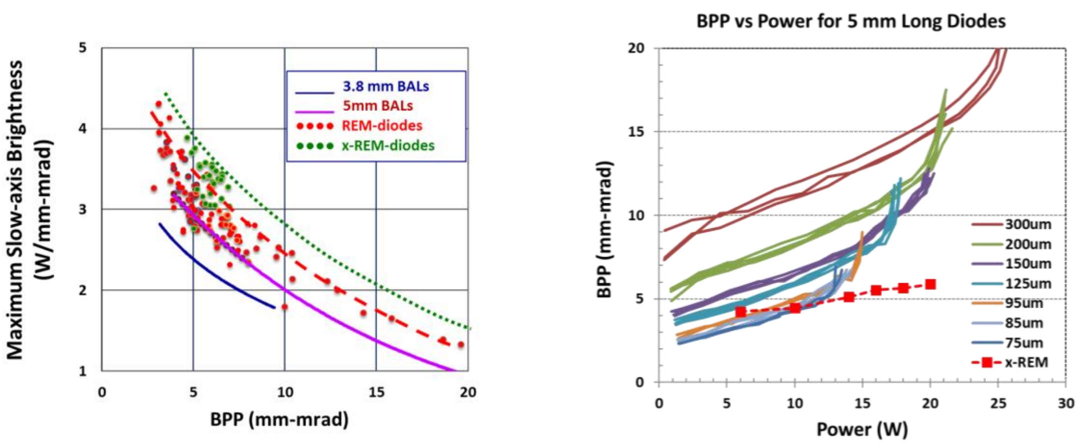


Figure 1: (Left) Plots showing maximum slow-axis brightness at a given beam-parameter-product (BPP) for regular broad area diodes (solid lines) for 3.8 mm and 5 mm long cavity devices compared to 5 mm long REM-diodes (dashed lines) at 915 nm and 976 nm and the brightness trend for the new x-REM (green dots and dotted line). (Right) Plots showing BPP vs ex-facet output power from various broad area lasers (solid lines) and improved BPP for x-REM (red squares).

REM-diode architecture is burgeoning to be a very versatile technology. This architecture allows augmenting additional means of stripping or suppressing higher order modes. As additional HOM suppression techniques are employed by inducing absorption and scattering, slow axis divergence remains relatively flat at even higher operating currents thus increasing the slow-axis brightness. For example, Figure 2 shows slow-axis divergence as low as 11 degrees even at ~20A. This ensued from a new technique we have just augmented to further suppress higher order modes. Although, only a few designs have been tried so far, we already see a significant improvement in slow-axis brightness. We refer to REM architecture implementing multiple HOM suppression techniques as the x-REM diode technology. Based on these results and the trend of our past findings, we project a new family of curves for the slow-axis brightness as a function of BPP as shown in Figure 1 (Left). This new scheme sets yet a new and higher brightness curve for REM-diode architecture. Multiple x-REM designs are being evaluated right now, with their typical power and efficiency performance shown in Figure 2 (Right). For example, a conventional BAL device produces 20 W at a BPP of about 15 mm-mrad. That same power can be produced from an x-REM device at a BPP of 5.5 mm-mrad instead. This is an improvement of 2.7 times in maximum brightness achievable with our new technology.

nLIGHT has made continuous advances in the power and brightness of broad-area lasers that form the building blocks of nLIGHT *element* products. This improvement trend for diodes developed for coupling into 105 µm and 0.15 NA fiber is plotted in Figure 3 (Left). In 2008 [1] we reported 100 µm BALs rated to 9 W of optical power. Current BALs are rated between 12 and 18 W [2]. Depending on the aperture width, REM and x-REM diodes can be reliably rated in the power range of 15 W to 20 W. 25W rated REM diodes designed for coupling into 105 µm and 0.15 NA fiber are currently under qualification. Their power and efficiency are shown in Figure 2 compared with regular 95 µm BALs.

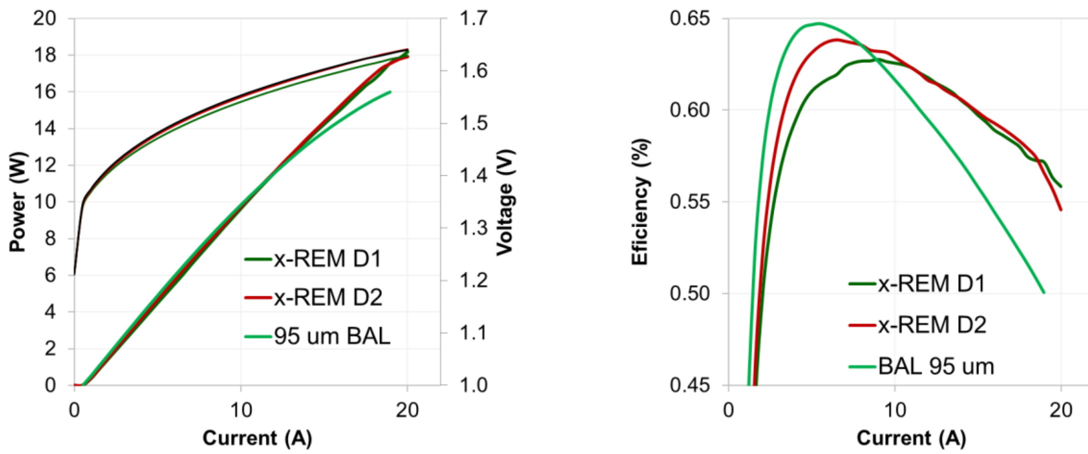


Figure 2: (Left) L-I-V and (Right) electrical-to-optical power conversion efficiency as a function of operating current, compared between BAL and x-REM-diodes designed for next generation of fiber-coupled nLIGHT *element* product with 105 µm and 0.15 NA beam.

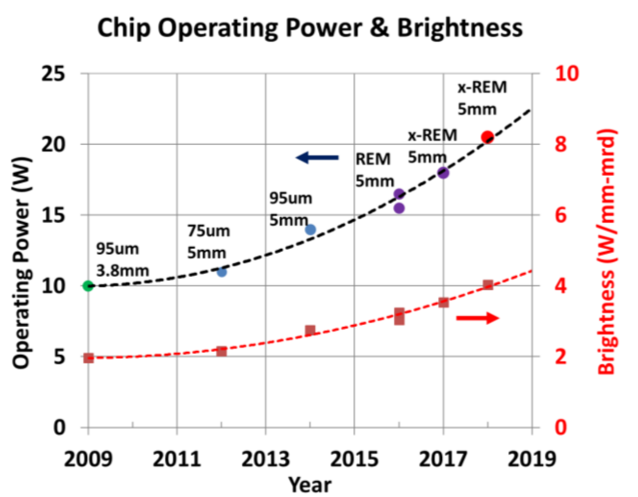


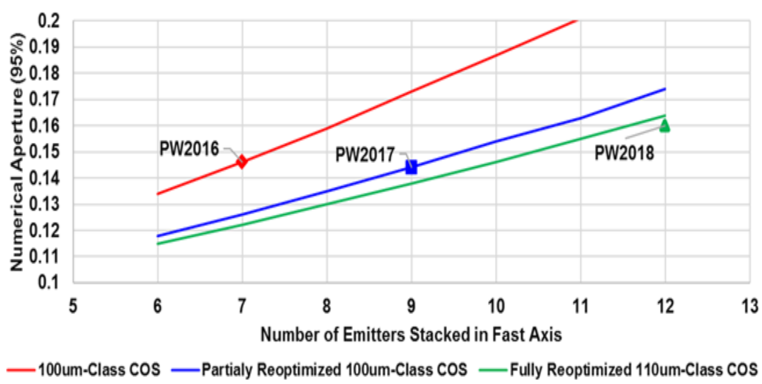
Figure 3: Plot showing improvement in chip operating power and brightness over time with nearly doubling of power and brightness over a period of approximately one decade.

FIBER-COUPLED PUMPS WITH REM AND x-REM DIODES

Using x-REM diode architecture, we have optimized fiber-coupled nLIGHT *element* packages to further scale up in output power and brightness [6-7]. The recent power increase coupled into a single 105 µm and 0.15 NA fiber is enabled by both the rise in x-REM chip brightness/power and the increase in number of chips coupled into a given numerical aperture.

Currently, state-of-the-art CWFL 105 µm-0.15NA pumps are typically using high-brightness emitters that are 90 to 120 µm in near-field diameter and a slow axis BPP of < 5 mm-mrad. About six or seven of these are typically stacked in the fast axis to achieve an overall BPP of < 7 mm-mrad. It has been challenging to stack more emitters in the vertical (fast) axis due to limitations to input excitation NA posed by pump combiners. During recent studies, we found eliminating the "dead space" (separation between the beams from the individual emitters) in vertical (fast) axis emitter stack could result in a ~40% fast-axis BPP reduction [11]. Since the spacing between emitters is driven by package alignment sensitivity, reliability, manufacturability, and minimizing optical loss, eliminating the dead spaces requires to re-optimize the optical-coupling system. A complete re-optimization requires an upgrade to the COS and epitaxial structure and rigorous design qualification are underway in 2018.

Last year we showed that theoretically there can be a total of 12 emitters stacked in the vertical direction of a 105 µm – 0.15 NA fiber, if all the dead spaces between emitters were eliminated. Re-optimization enabled an optical solution to extend the theoretical limit for both our current generation BAL devices and x-REM devices. 7 emitters represent the 2×7 nLIGHT *element* package released at Photonics West in 2016, with 155 W of power at 14 A. We reported a partially-reoptimized 2×9 nLIGHT *element* product release at Photonics West in 2017 [11], with ~200 W of power at 14 A, using the same BAL diode. Compared to BAL diodes, x-REM has sufficient design space left to pack more emitters in the fast axis. A fully optimized package based on the new x-REM emitter enabled 12-emitter per polarization fiber-coupled into 105 µm – 0.15 NA. The equations for modeling multiple emitters coupled into a given fiber diameter and NA are concisely stated by Yu, *et al* [12], and will not be repeated here. Using results for device BPP reported in [13-14] we plotted the excitation NA for 105 µm fiber as a function of the number of emitters in Figure 4. In 2016 we published how the original nLIGHT *element* optical design followed the trend plotted with the red line in Figure 4, 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. This year we have successfully coupled 12-emitters per polarization. These record milestones are plotted in Figure 4 and Figure 5 shows a record high power achieved by x-REM-diode technology in a polarization multiplexed 2×12 nLIGHT *element* package. Compared to the 2017 released product using 2×9 nLIGHT *element* [11] which had a rated power of 200 W at 14A and a maximum power of 272 W, x-REM-diode architecture has achieved ~315 W of maximum power at 17 A while maintaining a similar 105 µm/0.15 NA beam (95% power enclosure). This chip can be qualified as a product at 250 W from 105 µm/0.15 NA beam (95% power enclosure) at 920 nm.



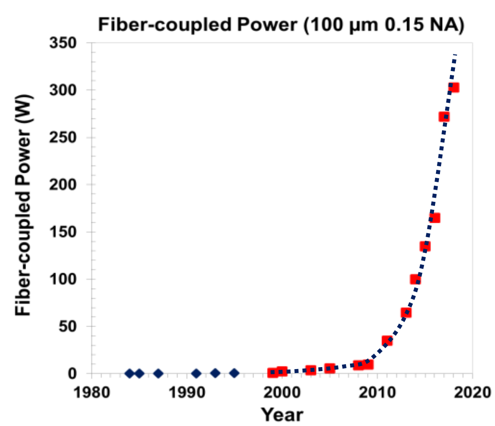


Figure 4: (Left) nLIGHT predicted fiber-coupled diode module numerical aperture as a function of number of emitters and design architecture. (Right) Resulting 105µm/0.15NA Fiber-coupled power trend over past two decades.

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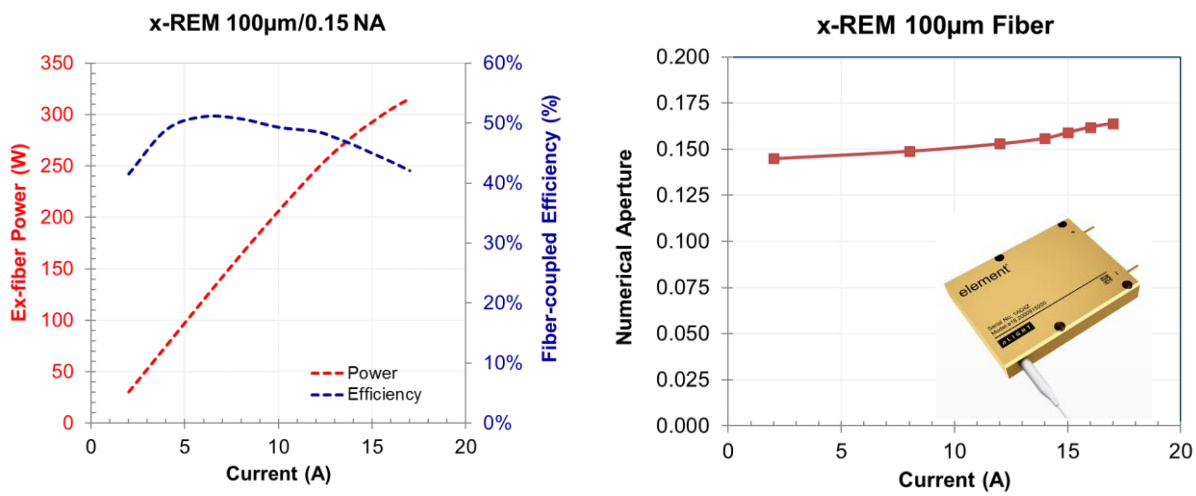

Figure 5: (Left) CW optical power and electrical-to-optical power conversion efficiency versus drive current for 2×12 nLIGHT *element* using 915 nm x-REM-diode chips coupled into 105 µm/0.15 NA beam producing record 315W at 17A with ~0.155 NA (95% power enclosure). (Right) Numerical Aperture versus current measured from 2×12 nLIGHT *element* package.

Last year [23] we reported on the extended life test of eight nLIGHT *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 nLIGHT *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.

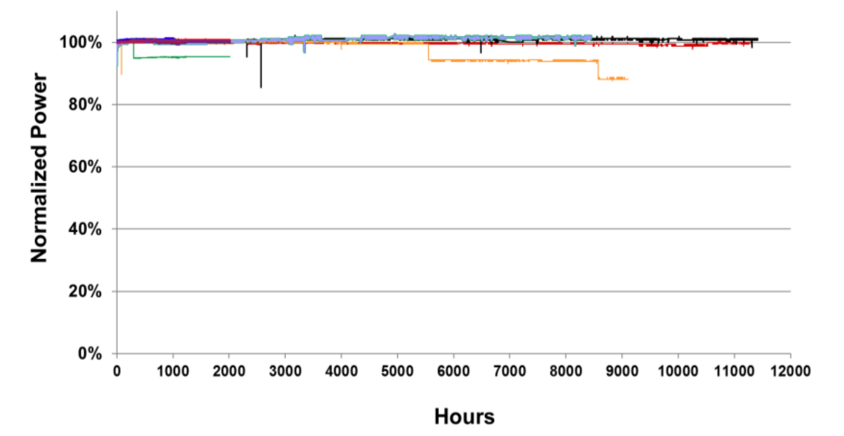

Figure 6. Normalized power for eight 200 W nLIGHT *element* e18s with 105 µm-0.22 NA fiber, with a 100 µm class COS, and one 225 W nLIGHT *element* e18 with 105 µm-0.22 NA fiber, with next generation 110 µm class COS, at 40 ˚C package temperature.

3. CONCLUDING REMARKS

During our study, we found the brightness degradation in larger aperture broad area lasers is fundamentally limited by the maximum allowed lateral modes. As a solution, nLIGHT fabricated a new architecture of broad area lasers called REM-diodes. The REM-diode architecture allows suppression of the higher order modes which enables use of larger emitters to scale power without compromising the slow-axis brightness. Inducing absorption or scattering preferentially to the higher order modes which is supplemented to the REM architecture, the so-called x-REM technology can further improve slow axis brightness by retaining a relatively flat slow-axis divergence at higher operating currents. The REM and x-REM ideas are agnostic to wavelength and thus have been demonstrated in our major diode products at wavelengths of 885nm, 915 nm and 976 nm with a range of emitter widths. To date, we have measured REM-diodes with brightness as high as 4.3 W/mm-mrad at a BPP of 3 mm-mrad. We also found eliminating "dead space" (separation between the beams from the individual emitters) eliminated in vertical (fast) axis emitter stack could increase the number of chips coupled into a given numerical aperture and thus a ~40% fast-axis BPP reduction. Applying x-REM chip architecture in such a re-optimized package design, a record high 315 W from a 915 nm 2×12 nLIGHT *element* with 105 µm/0.155 NA beam has been demonstrated. We also report a >11000 h package lifetest of 915 nm 2×9 nLIGHT *element* with REM chip. Our future directions will be focused on further improving thermal resistance, pushing the x-REM brightness and on-chip geometrical multiplexing scheme.

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