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High Brightness Diodes and 600W 62% Efficient Low SWaP Fiber-coupled Package

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ABSTRACT

In this paper, we show results of 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 new extra Reduced-mode (x-REM) diode design providing a record ~363 W output from a 2×12 nLIGHT *element*® in 105 µm diameter fiber. There is also an increasing demand for low size, weight and power-consumption (SWaP) fiber-coupled diodes for compact High Energy Laser (HEL) systems for defense and industrial applications. Using thirty single emitters that were geometrically- and polarization-combined, we have demonstrated 600 watts and 62% efficiency at in 225 µm/0.22 NA fiber resulting in specific mass and volume of 0.44 kg/kW and of 0.5 cm^3/W respectively. Furthermore, we have increased the number of chips to forty and increased the output power to 1kW and 52% in the same fiber diameter and numerical aperture. This results in a fiber-coupled package with specific mass and volume of <0.18 kg/kW and <0.27 cm^3/W, respectively.

Key words: Fiber-coupled diode laser, high brightness, pump diodes, diode laser brightness, REM-diodes, Low SWaP diodes, 976 nm diodes

1. INTRODUCTION

There is an increasing demand for high-power, high-brightness diode lasers from 8xx nm to 9xx nm wavelength range for applications such as fiber laser pumping, materials processing, solid-state laser pumping, and consumer electronics manufacturing. The kilowatt CW fiber laser pumping (915 nm - 976 nm) requires the diode lasers to have both high power and high brightness to achieve high-performance and reduced manufacturing costs. Spectral-beam-combined or coherently-combined HEL systems using fiber amplifiers require diode lasers with low size, weight and power-consumption (SWaP) for them to be practical in mobile platforms in rugged military environments. This paper presents progress in the development of high brightness diode laser chips and high brightness fiber-coupled product platform, *element*®. The kilowatt CW fiber laser pumping (at 915 nm for industrial fiber lasers [1] & at 976 nm for HEL fiber amplifiers [2]) particularly requires the diode lasers to have both high power and high brightness to achieve high-performance. In the past several decades, the amount of power coupled into a fixed fiber diameter and numerical aperture has increased exponentially mimicking Moore's Law [3-5]. Further brightness improvement and power-scaling have been enabled by both the rise in chip brightness as well as the increase in the number of chips used to couple into a given numerical aperture.

These laser diodes have become very compelling for use in fiber lasers that are needed in industrial and defense applications. Recent technology advances in electrically-based solid-state and especially fiber lasers have shown improved power levels and efficiency paving the path towards deployable >100kW class HEL Systems. However, to further scale up in power and to use them in a wide variety of mobile platforms, these diodes must be packaged in a lower SWaP configuration and much higher efficiency.

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

We have designed a new class of broad area lasers called Reduced-Mode-diode (REM-diode) that allows further scaling up of slow-axis brightness [4, 16-17]. nLIGHT's REM-diode architecture allows suppression of higher order lateral modes which enables use of larger emitters to scale power without compromising the slow-axis brightness resulting in inherently higher brightness compared to regular broad area lasers. We achieved this by reducing the thermal lensing effect and reducing the allowed number of modes in the slow-axis direction primarily by spatial filtering of the lateral modes. Recently, we have found that additional lateral higher order mode suppression techniques can be supplemented to the REM-diode spatial filtering concept by introducing scattering, absorption and lateral-leakage mechanisms to preferentially further suppress higher order modes. We refer to these new REM diodes as x-REM diodes to denote extra mode suppression methods that are implemented. nLIGHT fabricated x-REM diodes with a range of emitter widths in this study and compared them to standard broad area lasers. Invariably, the x-REM-diodes display lower slow-axis divergence. This allows us to operate x-REM-diodes with larger emission widths resulting in larger pumped areas. As a result, for the same beam-parameter-product (BPP), the thermal footprint of these devices is larger thus making the thermal and the series resistances lower. Consequently, the rollover power is higher for these devices and the efficiency does not drop off as quickly as the standard devices. Therefore, the x-REM-diodes are more efficient at the same operating powers.

Latest x-REM chip designed for coupling into 105 µm fiber and an equivalent conventional BAL performance suitable for the same application are compared in Figure 1 (Left). This x-REM chip's slow-axis brightness and equivalent BPP as a function of current are shown in Figure 1 (Right).

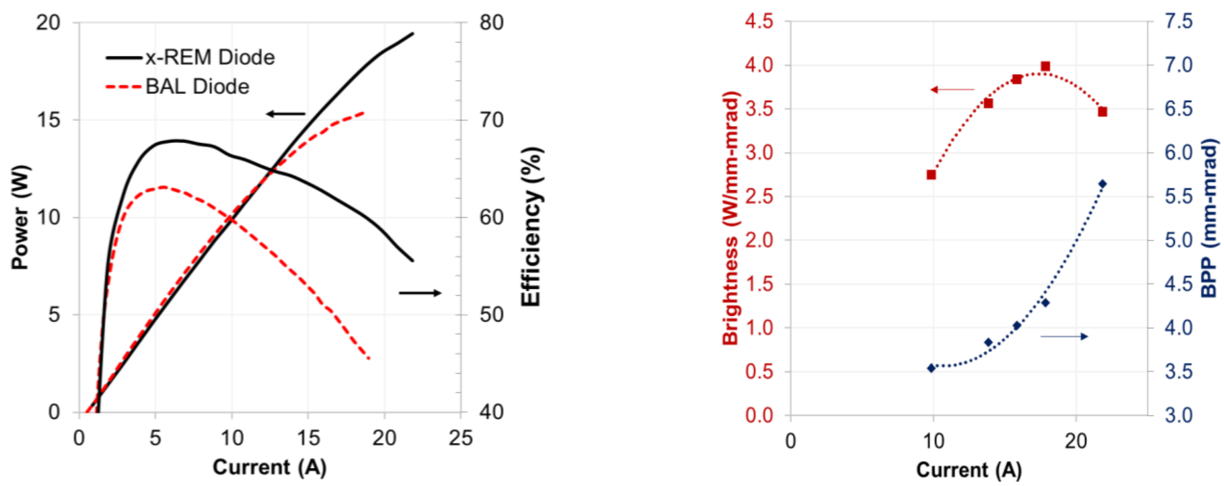
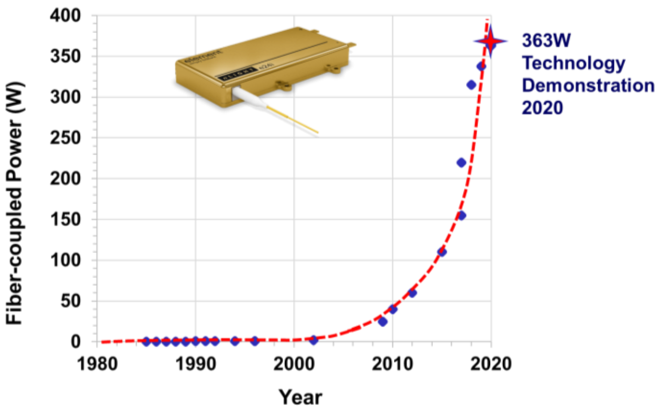


Figure 1: *(Left) L-I and electrical-to-optical power conversion efficiency as a function of operating current, compared between BAL and x-REM-diodes designed for next generation of fiber-coupled nLIGHT element package with 105 µm and 0.15 NA beam (Right) Slow-axis brightness and BPP as a function of current. Maximum brightness of 4 W/mm-mrad and BPP of 4.3 mm-mrad was achieved at the operating current of 18A.*

FIBER-COUPLED PUMPS WITH 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]. Currently, state-of-the-art 105 µm-0.15NA diode pumps are using high-brightness emitters that are 95 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. Reducing the "dead space" in the vertical axis emitter stack provides ~40% fast-axis BPP reduction [11]. Compared to BAL diodes, x-REM diode has sufficient design space left to pack more emitters in the fast axis. A fully optimized package based on the new x-REM emitter allows 12-emitter per polarization fiber-coupled into 105 µm diameter fiber. These record milestones are plotted in Figure 2 (Left). Figure 3 (Right) shows a record high power achieved by x-REM-diode technology in a polarization multiplexed 2×12 nLIGHT *element* package demonstrating ~363 W.



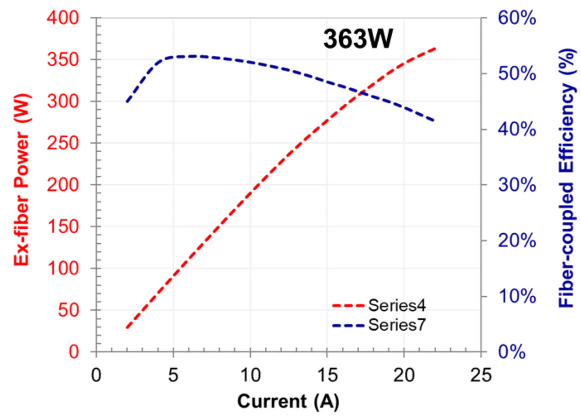


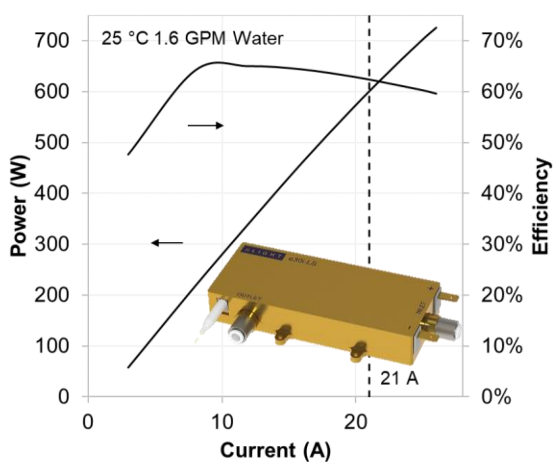
Figure 2: (Left) Plot showing improvement in fiber-coupled power from 105 µm diameter fiber over four decades. (Right) Output power as a function of current from 105 µm diameter fiber.

LOW SWaP FIBER-COUPLED DIODE LASER PUMPS

HEL continues to offer promise as a transformational "game changer" technology as the Department of Defense encounters new asymmetric and disruptive threats, while facing increasingly sophisticated traditional challenges. Recent advances in combinable fiber amplifiers have shown improved power levels and efficiency paving the path towards deployable >100kW class HELs. For many DoD applications, SWaP is still too large for deployment of HEL systems for ground, sea and airborne applications. In the past, most fiber-coupled laser diode pumps have been developed for large volume industrial applications where the primary metrics are price-per-bright-watts and reliability. While these metrics are also important for the DoD applications, there are a few other metrics that are indispensable, namely, SWaP, efficiency and reliable operation under harsh Military conditions. Typically, the size and weight of these packages are two times greater than required. Furthermore, the brightness and efficiency of laser diodes that are good enough for industrial applications are often inadequate for this application. Additionally, single fiber amplifier channel power continues to increase and R&D effort to produce >3 kW fiber amplifiers is already underway. Hence, diode laser pumps with enough brightness and efficiency as well as low SWaP capable of producing, at least, >3 kW are in demand. There are specifically three metrics that confront a considerable gap. Industrial diode lasers have approximately >1 kg/kW specific mass and specific volumes are greater than two times what would be acceptable for HEL applications. Furthermore, industrial diode lasers are at approximately 50% ex-fiber electrical-to-optical power conversion efficiency (PCE); whereas, HEL applications require ex-fiber PCE $\geqslant$ 55%. To address these key technical gaps, we have developed innovative diode laser chip and opto-mechanical packaging technology.

We designed a pump optical-combining method that comprises two rows of fifteen diode laser chip-on-submounts (CoS). These CoS's have very high thermal conductivity and they are mounted on a stair-step for a simple and mechanical geometrical combining architecture. Each diode is collimated by using fast-axis and slow-axis collimating lenses. These fifteen beamlets are then directed towards the polarization multiplexer using a turning mirror for each beam. After the turning mirrors, each row of fifteen beams are vertically stacked with nearly full fill-factor and directed towards polarization multiplexer with the aid of 90° reflecting mirrors. Subsequently, the two rows of fifteen compacted-beamlets are combined using a polarization multiplexer to achieve 2x brightness and these beams are then focused into a fiber using a combination of telescope and focusing lens. Since each beamlet is individually lensed, we can achieve superb beam-pointing not possible with bar-based fiber-coupled packaging technology. Bars have inherent "smile" issues which result in "rogue" beams that are not unidirectional thus degrading beam quality thus introducing high numerical-aperture cladding-light when coupled into fibers. This is significantly different for nLIGHT's optical assembly. It can achieve under-filled numerical aperture and spot size when focused into a fiber. This eliminates the need for actively cooling the delivery fiber. This optical combining method is very efficient, and it conserves volume since no large opto-mechanical components are required to arrange the beamlets into a compact and nearly 100%-fill-factor collimated beam format. nLIGHT has been using this *element*® optical combining technique for most of its products. Here, we have increased the fill-factor in the collimated space to near theoretical limit without incurring scattering loss.

The low SWaP package we have developed, utilizes lower density material compared to copper for the housing body and higher thermal conductivity components where the materials encounter large heat flux. Current *element*® package has a thermal resistance of 3.3 C/W and specific mass of 1.65 g/W, which prevents the package from delivering power more than 400 W at 50% PCE even when using the high brightness high efficiency single emitter diodes. The low SWaP package uses highly thermally conducting and CTE-matched submounts for the diode chips. It allows for water or ethylene-glycol-water (EGW) or propylene-glycol-water (PGW) as a coolant. Cooling plenum is integrated inside the package. The package has an effective thermal resistance of 1.6 C/W. Coolant can flow in the range of 0.5 GPM to 1.5 GPM and below 7 PSI pressure rise within the package. We have demonstrated 600 W output power with 62% ex-fiber efficiency at 25C and 1.6 GPM water flow (see Figure 3) in 220 μm fiber with 0.17 NA beam. The specific mass and specific volume of this package is 0.44 kg/kW and 0.5 cm^3/W (footprint including electrical and coolant ports) respectively.



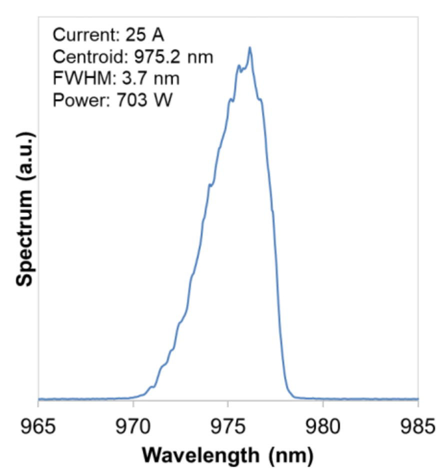


Figure 3: (Left) L-I and ex-fiber electrical-to-optical power conversion efficiency as a function of operating current of nLIGHT's e-30i-LS package (inset) at 25C and 1.6 GPM of water flow (Right) spectral output of 3.7 nm at FWHM at 25A.

We have also fabricated another package with a higher number of chips. In a forty-emitter version of this low SWaP package, we have demonstrated 1kW output power in 220 μm fiber with 0.22 NA (see Figure 4). At this power the efficiency is 52%. The fiber coupling efficiency is greater than 92%. Such a high fiber coupling efficiency allows us to use uncooled fiber mounts. The specific mass and specific volume of this package amounts to 0.18 kg/kW and 0.27 cm^3/W respectively.

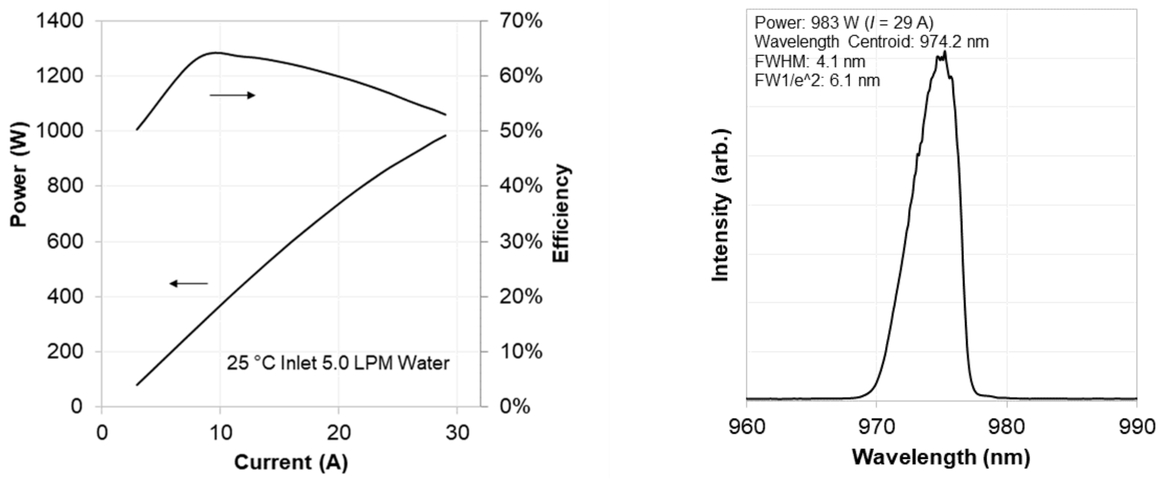


Figure 4: (Left) L-I and ex-fiber electrical-to-optical power conversion efficiency as a function of operating current of nLIGHT's e-40i-LS package at 25C and 5 LPM of water flow (Right) spectral output.

CONCLUDING REMARKS

It has become apparent that brightness degradation in larger aperture broad area lasers is fundamentally limited by the maximum number of 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. 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 ~363 W from a 976 nm 2×12 nLIGHT *element* in 105 μm diameter fiber. We have also designed and demonstrated a low SWaP fiber-coupled package with in-fiber power of 600 W and 62% electrical-to-optical efficiency at 25C. This package has a specific mass of 0.44 kg/kW and a specific volume of 0.5 cm^3/W. By increasing the number of single emitters to forty, we have demonstrated 1kW with 52% electrical-to-optical efficiency at 25C in 220/0.22 NA fiber resulting in specific mass and volume of 0.18 kg/kW and 0.27 cm^3/W respectively.

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REFERENCES

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

[2] I. Dajani, C. Zeringue, C.Lu, C. Vergien, L. Henry, and C. Robin,” Stimulated Brillouin scattering suppression through laser gain competition: scalability to high power,” Optics Letters, Vol. 35, pp 3114 (2010).

[3] M. Kanskar, S. Keeney, R. Martinsen, “Laser Diodes: The power of brilliance- the past and future of high-power semiconductor lasers”, Laser Focus World, Vol. 54, No. 1, pp 69 (Jan 2018).

[4] M. Kanskar, L. Bao, Z. Chen, M. Hemenway, D. Dawson, M. DeVito, W. Dong, M. Grimshaw, X. Guan, K. Kennedy, R. Martinsen, W. Urbanek, S. Zhang,” High-brightness diodes and fiber-coupled modules”, Proceedings Volume 9348: High-Power Diode Laser Technology and Applications XIII (2015).

[5] 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, “High reliability of high power and high brightness diode lasers”, Proceedings Volume 8965: High-Power Diode Laser Tech. and Apps. XII (2014).

[6] 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).

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

[8] K. Kennedy, M. Hemenway, W. Urbanek, K. Hoener, K. Price, L. Bao, D. Dawson, M. Kanskar, J. Haden, “High-power fiber-coupled diode lasers with superior brightness, efficiency, and reliability”, Proceedings Volume 8965: High-Power Diode Laser Technology and Applications XII (2014).

[9] M. Kanskar, L. Bao, Z. Chen, M. Hemenway, D. Dawson, M. DeVito, W. Dong, M. Grimshaw, X. Guan, K. Kennedy, R. Martinsen, W. Urbanek, S. Zhang,” High-brightness diodes and fiber-coupled modules”, Proceedings Volume 9348: High-Power Diode Laser Technology and Applications XIII (2015).

[10] 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, “High reliability of high power and high brightness diode lasers”, Proceedings Volume 8965: High-Power Diode Laser Tech. and Apps. XIII (2014).

[11] J. G. Bai, et al., “Mitigation of thermal lensing effect as a brightness limitation of high-power broad area diode lasers,” *Proc. SPIE*, Vol. 7953, pp. 79531F, Jan. 2011.

[12] J. Piprek, “Inverse Thermal Lens Effects on the Far-field Blooming of Broad Area Laser Diodes”, *IEEE Phot. Tech. Lett.*, Vol. 25, pp. 958 -960, May 2013.

[13] H. Eckstein, U. D. Zeitner, A. Tünnermann, W. Schmid, U. Strauss, and C. Lauer, “Mode shaping in semiconductor broad area lasers by monolithically integrated phase structures”, Opt. Lett, vol. 38, no. 21, p. 4480, 2013.

[14] M. Hemenway, W. Urbanek, D. Dawson, Z. Chen, L. Bao, M. Kanskar, M. DeVito, D. Kliner, R. Martinsen, “Advances in High-Brightness Fiber-Coupled Laser Modules for Pumping Multi-kW CW Fiber Laser”, PW2017.

[15] H. Yu, Y. Liu, A. Braglia, G. Rossi, G, Perrone, “Investigation of collimating and focusing lenses’ impact on laser diode stack beam parameter”, Applied Optics, Vol. 54, No 34, p. 10240 - 10248

[16] M. Hemenway; W. Urbanek; D. Dawson; Z. Chen; L. Bao; et al, “Advances in high-brightness fiber-coupled laser modules for pumping multi-kW CW fiber lasers”, Proc. SPIE, Vol. 10086, February 2017.

[17] M. Kanskar, L. Bao, Z. Chen, D. Dawson, M. DeVito, et al, “Continued Improvement in Reduced-mode (REM) Diodes Enable 272 W from 105 µm 0.15 NA Beam”, Proc SPIE, Vol. 10086, February 2017