100-W, 105-µm, 0.15NA Fiber Coupled Laser Diode Module

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ABSTRACT

We report on the development of a high brightness laser diode module capable of coupling over 100W of optical power into a 105 µm 0.15 NA fiber at 976 nm. This module, based on nLIGHT's Pearl™ product architecture, utilizes hard soldered single emitters packaged into a compact and passively-cooled package. In this system each diode is individually collimated in the fast and slow axes and free-space coupled into a single fiber. The high brightness module has an optical excitation under 0.13 NA, is virtually free of cladding modes, and has an electrical to optical efficiency greater than 40%. Additionally, this module is compatible with high power 7:1 fused fiber combiners, and initial experiments demonstrated 500W coupled into a 220 µm, 0.22 NA fiber. These modules address the need in the market for higher brightness diode lasers for pumping fiber lasers and direct material processing.

Keywords: fiber laser pump, fiber coupled diode laser, high brightness, diode laser, tapered fiber combiner

1. INTRODUCTION

Industrial applications and fiber laser pumping have demonstrated an increased need for higher brightness fiber coupled diode lasers. Higher brightness pump sources enable higher power fiber lasers through the ability to spatially combine a greater number of pumps and more efficiently couple them into the fiber. Pulsed fiber lasers also require high brightness pump modules to reduce the active fiber length and corresponding fiber nonlinearities. Managing nonlinearities in pulsed fiber lasers enables lasers with shorter pulse lengths and higher peak power.

Traditional fiber coupled diode lasers have been based either on bars or fiber coupled single emitters[1,2,3,4]. In bar-based systems, the asymmetric beam quality in the fast and slow axis requires the use of expensive micro-optical beam shaping systems. These systems, which rotate the fast and slow axes of individual emitters in the laser bar, are typically implemented with the use of step mirror arrays or arrays of micro-optical cylinder lens telescopes rotated by 45°. While these systems are effective at rotating the optical axes, the optical to optical efficiency is diminished by multiple optical interfaces, imperfect beam rotation, and low fill factor after rotation. The brightness of bar-based systems is further limited due to emitter cross heating and bar "smile." Cross heating increases the effective thermal resistance, forcing the individual emitters within the diode laser bar to run at lower power to maintain a reasonable junction temperature. While high overall powers can be achieved, the linear power density of each emitter, and hence the brightness, is reduced. Bar smile introduces fast axis pointing error and optical defocusing, further diminishing optical to optical efficiency.

Pump modules based on fiber coupled single emitters are not subject to device cross heating, and are thus able to operate at very high power densities while maintaining a low junction temperature. However, traditional single emitter packages coupled to a single fiber suffer from a large decrease in beam quality as the diffraction limited fast axis is coupled to a multimode fiber. In other words, while the diodes themselves are able to operate with higher brightness than bar-based systems, fiber coupled single emitter packages significantly under fill the fiber in the fast axis, leading to low overall system brightness. Power scaling is typically achieved through the use of fused-tapered fiber combiners. However, the optical scattering loss and brightness losses of these combiners further reduce the already low beam quality of fiber coupled single emitters.

nLIGHT has developed a novel approach to achieve extremely high brightness fiber coupled diode lasers. Our product is based on high power broad area single emitters, free space combined in an elegant and inexpensive manner. This approach provides the high power and high brightness operation of individual emitters, while achieving the high power levels of bar-based systems. Each device is bonded, tested, and screened, insuring excellent device performance with superb reliability. The single emitters are capable of being run at high linear power density, increasing the brightness of the diode laser system. Finally, the optics are designed to efficiently image the diode laser onto the fiber, maintaining the brightness and high system efficiency of the single emitter diode lasers. The result of this package is a system that is unsurpassed in terms of electrical to optical efficiency and system brightness.

2. HIGH BRIGHTNESS BROAD AREA LASERS

The industry has recently made remarkable advances in the brightness and power of broad area diode lasers[4,5,6]. Peak power levels from a single emitter diode laser with a 100um emitting facet has been demonstrated in excess of 20 W, corresponding to reliable operation at over 10 W. nLIGHT has developed its own line of 100um single emitters rated at 9 W at 976 nm. These devices are hard soldered on expansion matched submounts, with proven long term reliability of over 450K MTTF corresponding to a 2200 FIT with a 90% confidence level. Each of nLIGHT's devices is individually screened by high power test, accelerated burn-in, and stringent visual inspection. A typical LIV curve is shown below in Figure 1.

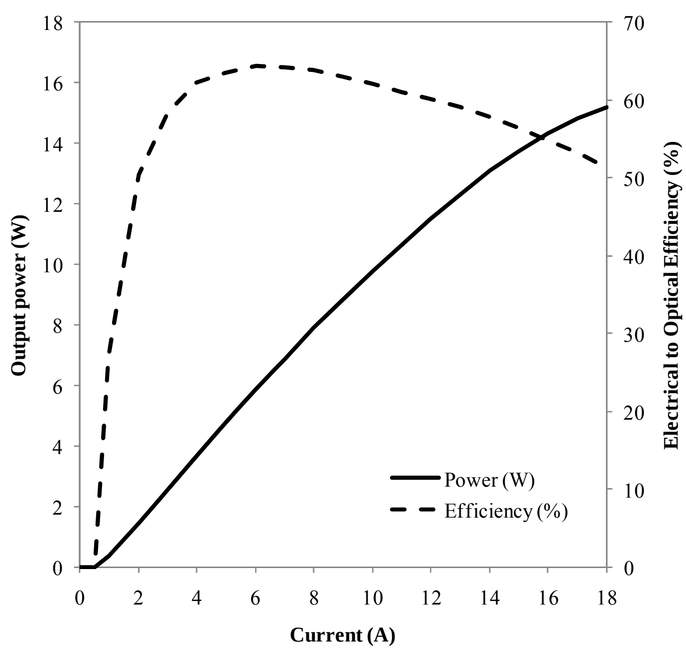

***Fig. 1**: LI and efficiency curves for a single emitter diode laser developed at nLIGHT. Such a device is rated at over 9 W of optical power with a FIT rate of 2200 at 90% confidence level.*

3. PEARL ARCHITECTURE

nLIGHT's patented line of fiber coupled multiple single emitter packages is called Pearl[7]. The emitters are stacked in a stair-step manner to provide an excellent thermal path from the diode to the cooling plate, maintaining a low junction temperature. This mechanical arrangement conveniently stacks the emitters in the fast axis, maintaining the brightness of the diode lasers. Each diode is individually collimated with fast axis and slow axis lenses, resulting in unsurpassed pointing accuracy and an excellent optical "fill factor." The geometry of the emitters and corresponding optics is arranged to reduce "dead space" between each emitter, maximizing diode brightness. The step height and FAC lens focal length are optimized for the system design. The fill factor is maximized for high brightness packages, and reduced to loosen manufacturing tolerances for low brightness packages. After each emitter is collimated with a FAC and SAC lens, rhombus prisms spatially combine columns of emitters. Additionally, a polarization combiner can be used for significant brightness improvements. Simple focusing lenses couple the collimated beams into the fiber at the appropriate numerical aperture. The flexible packaging method scales to high power by accommodating multiple rows or columns of emitters. In addition, the packages accommodate various emitter widths and wavelengths. Applications such as multispectral imaging or dual wavelength pumping benefit from the ability to couple multiple wavelengths into the same fiber.

Based on the Pearl™ product line, nLIGHT has demonstrated a range of pump modules with excellent system brightness. Figure 2 shows a comparison of 9xx nm Pearl pump modules with other commercially available diode pump modules.

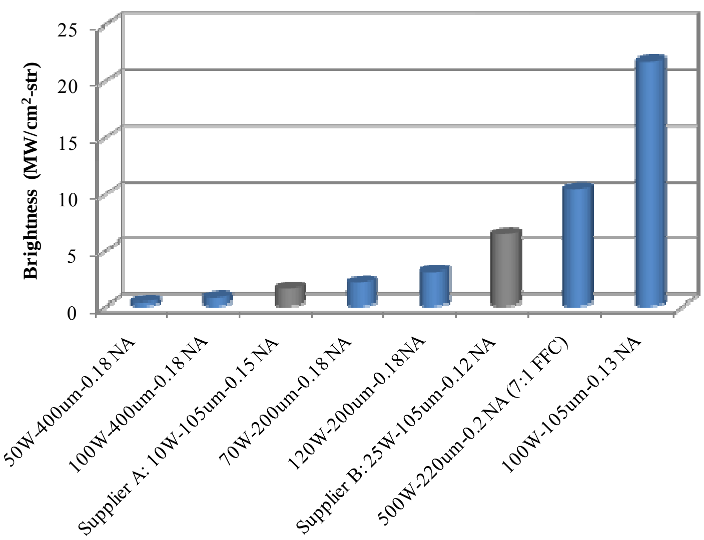

***Fig. 2**: Diode laser brightness (MW/cm^2-str) for various diode laser pump modules. Brightness levels in excess of 21 MW/cm^2-str have been achieved using nLIGHT's Pearl product line.*

This diode brightness has not come at the expense of system efficiency. There has been much work in recent years to increase the efficiency of diode lasers[8,9]. The Pearl product line maintains this excellent efficiency through an optical design with high fiber coupling efficiency, resulting in a package with extremely high overall electrical to optical efficiency. For instance, nLIGHT has developed a system capable of achieving a 60% operating efficiency at 90 W at 940 nm, measured at the distal end of a 400 µm fiber, as demonstrated in Figure 3. This result is made possible through optical to optical efficiency in excess of 97%. These high efficiencies are also available for higher brightness fiber laser pump modules. The electrical to optical efficiency for a 70 W, 200 µm pump module is routinely demonstrated to be in excess of 55% at the operating point, with less than 1% of the optical power in the cladding.

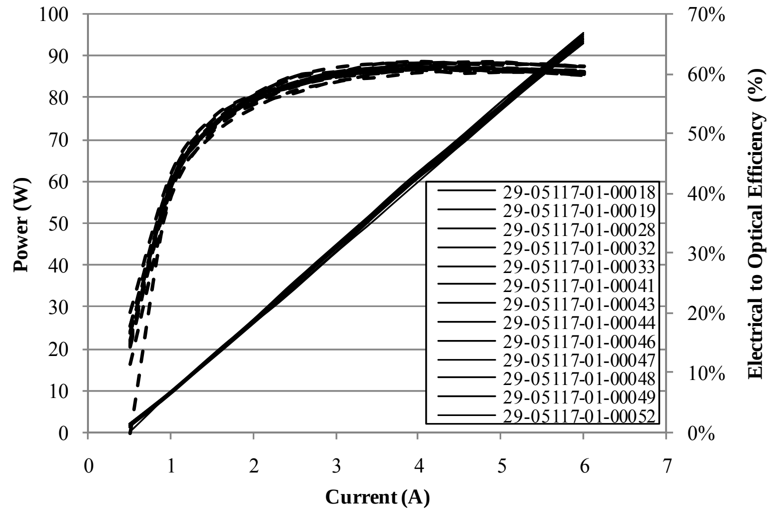

***Fig. 3**: High efficiency Pearl modules with system efficiency in excess of 60% for all devices.*

In terms of spectral brightness, nLIGHT has chosen to narrow and stabilize the spectral linewidth of the Pearl modules with the use of volume Bragg gratings (VBGs). Due to the excellent collimation achievable with the Pearl product line, either single point VBG locking or the locking of individual emitters can be easily implemented. nLIGHT has decided to pursue VBGs for spectral stabilization for several reasons. First, VBGs allow for the optimization of diode laser design in terms of power and efficiency, and allow for a simple production process with high yields. Second, VBGs allow for independent control of linewidth and temperature stability range. Third, the diode efficiency can be maintained through the judicious choice of front facet and VBG reflectivity[10]. Finally, VBGs can used in bar-based and single-emitter packages with ease, and can be implemented into fast axis lenses[11].

The performance over temperature of a VBG-stabilized 5-emitter Pearl module, emitting at 879 nm, is shown below in Figure 4. The VBG gratings effectively lock the spectrum to 879 nm over the range from 20 to 40°C, at 45°C the material gain is sufficiently far away to introduce parasitic lasing on the Fabry-Perot cavity modes. As can be seen, the electrical to optical efficiency remains well above 50% over the entire temperature range.

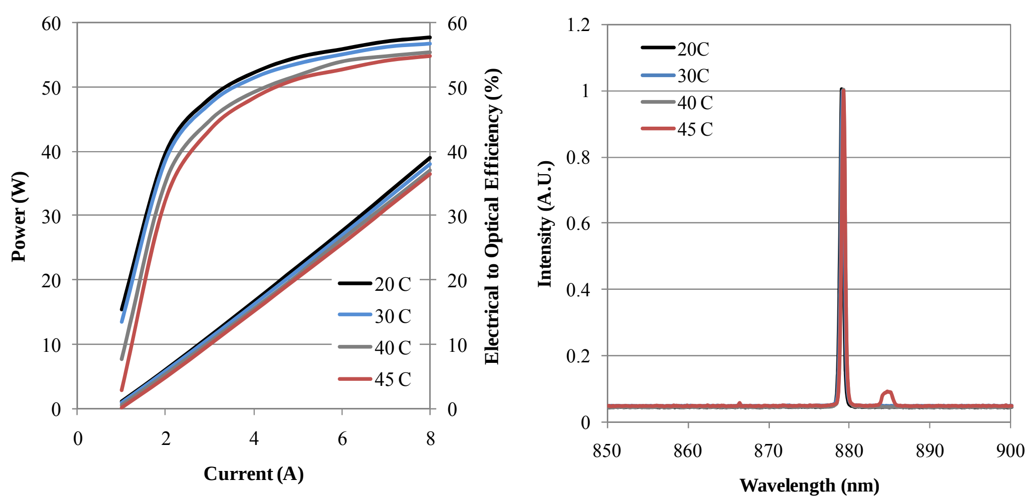

***Fig. 4**: (left) LI and efficiency curves for a 5-emitter Pearl module with VBG gratings as measured at 20, 30, 40 and 45 °C. (right) The spectrum remains locked at 6 A of operating current from 20-40 °C. Parasitic lasing on the Fabry-Perot modes is observed when operating at 45C.*

4. HIGH BRIGHTNESS PACKAGE

Building on the proven manufacturing successes of lower brightness Pearl products, nLIGHT is now developing a high brightness Pearl package capable of coupling up to 14 emitters into a 105 µm, 0.15 NA fiber. This diode pump was designed to be a building block module which maintains compatibility with high power fiber combiners. For instance, a 7:1 fiber combiner rated at 1 kW was demonstrated by ITF Laboratories last year[12]. Our task is to couple as many emitters as possible to this fiber, while maintaining a cost structure compatible with reduced $/W targeted by fiber laser manufacturers.

The maximum number of emitters that can couple into a specific fiber is found by dividing the beam parameter product (BPP) of the fiber by the BPP of the single emitter. This is performed in both the fast and slow axis, as shown in equations (1) and (2). The fill factor of the array must also be considered, as well as the fact that the spot size is generally square while the fiber is circular, in both the near field and far field:

$$N_{FA} \cong \frac{D_f \theta_f}{2\omega_{FA}\theta_{FA}} \gamma_{FA} \tag{1}$$

$$N_{SA} \cong \frac{D_f \theta_f}{2\omega_{SA}\theta_{SA}} \gamma_{SA} \tag{2}$$

In Equations 1 and 2, N_{FA} and N_{SA} are the number of emitters in the fast axis and slow axis respectively, D_f and θ_f are the fiber diameter and full angle, ω_{FA} and θ_{FA} are the fast axis collimated beam width and divergence angle and γ is the fill factor. The factor of 2 accounts for the geometry of coupling a square beam in a round fiber, as the spot size at the fiber must be $\sqrt{2}$ less than the fiber core, and the launch angle must also be $\sqrt{2}$ less than the fiber NA.

Using equations (1) and (2), we estimated a maximum of 7 rows and 1 column of emitters, with an option to polarization combine a second column. Our first prototypes utilize a pair of crossed cylinder lenses for fiber coupling, as shown in the ray trace in Figure 5.

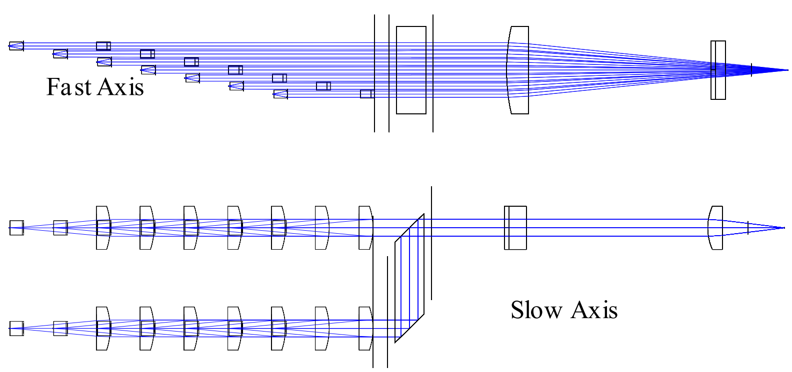

Fig. 5*: The ray trace for a 14-emitter Pearl module capable of coupling over 100W of optical power into a 105 µm, 0.15 NA fiber. The two columns of light are combined using polarization multiplexing. The collimated light is focused with a crossed cylinder pair of optics.*

The maintenance of high coupling efficiency over a broad current and temperature range requires high stability of the fast and slow axis beam quality. nLIGHT has developed a precision lensing technique where pointing error of the individual emitters is less than 0.1 mrad and 0.5 mrad in the slow and fast axes, respectively. The uniformity in beam divergence over current is shown in Figure 6.

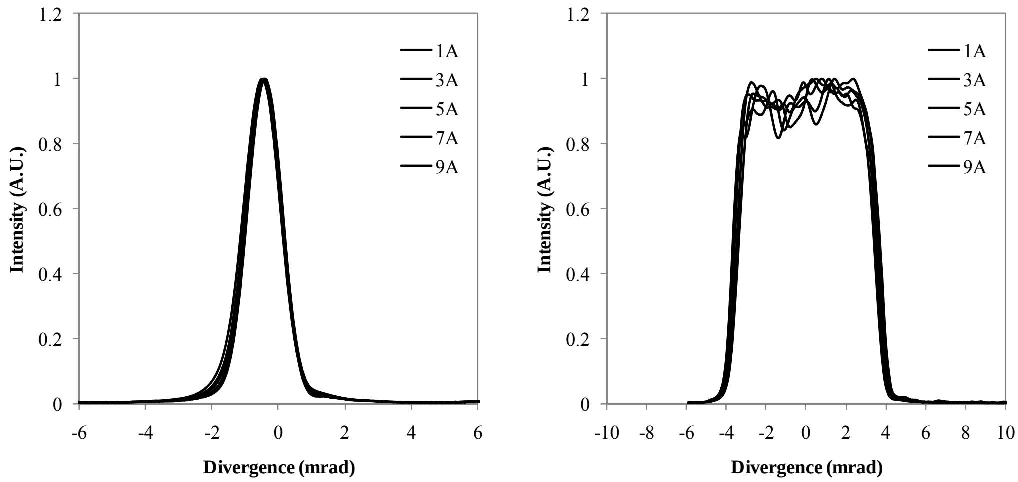

Fig. 6*: (left) Fast axis divergence as a function of current (right) Slow axis divergence as a function of current. Excellent pointing tolerance and stability over a wide range of current is maintained.*

The LI curves for 7 prototypes of a 100 W, 100 µm, 0.15 NA Pearl module are shown in Figure 7. All of the devices are able to achieve over 100W of "cladding free" power. The electrical to optical efficiency maximum is approximately 45%, with operating efficiency at approximately 35% at 100W. At 100W output power and a 90% power enclosure at 0.13 NA, the system brightness is estimated to be in excess of 21 MW/cm^2-str, as calculated using equation (3):

$$B = \frac{P}{\pi \frac{D^2}{4} \pi \theta^2} \qquad (3)$$

where B is the brightness, P is the output power, D is the fiber core diameter, and θ is the fiber half angle.

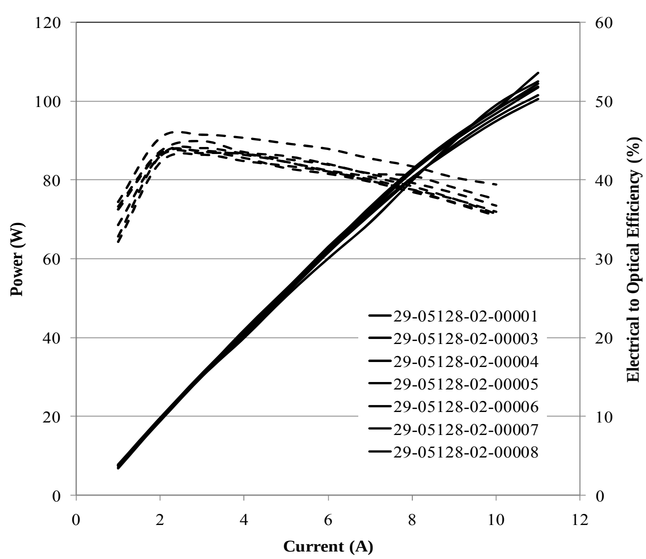

Fig. 7*: LI and efficiency curves for 14-emitter Pearl modules demonstrating >100W output power for 105um 0.15NA fiber.*

nLIGHT has demonstrated these results with both free-running and VBG-locked diode lasers. Because each diode is individually tested and screened, the aggregate spectral width of a 14-emitter package is approximately the same as that of a single diode. VBGs can be used to further narrow the spectrum, and add wavelength stability to the diode array, as shown in Figure 8.

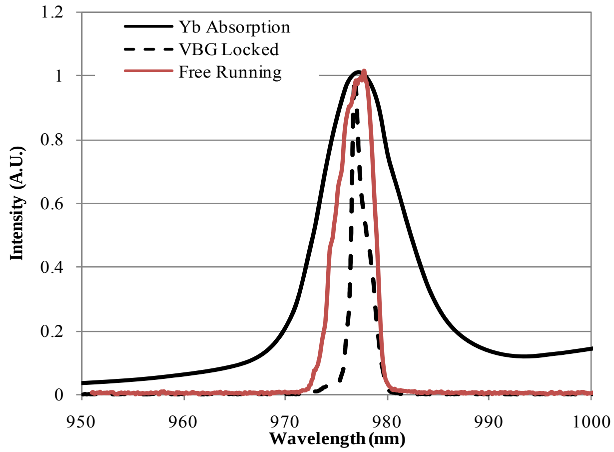

Fig. 8*: Spectral characteristics of a 14 emitter Pearl module. As the single emitters are individually tested and matched, an extremely narrow free-running spectrum is achieved. VBGs can be used to further stabilize and narrow the spectrum. In both cases, free-running and VBG locked, the spectrum fits nicely within the Yb absorption line.*

5. FUSED TAPERED FIBER COMBINER RESULTS

Seven of these 14 emitter packages were coupled to an ITF 7:1 fused tapered fiber combiner, part number MMC070110E1, with an output of 220 µm, 0.22 NA and rated at 100 W per input port. The coupling efficiency for each channel was measured with a separate fiber, and then an input fiber from the combiner was aligned to each box. The combined power versus current curve is shown in Figure 9. At 10.5 A of current, over 500 W of optical power was achieved. This represents a system brightness of just under 10 MW/cm^2-str.

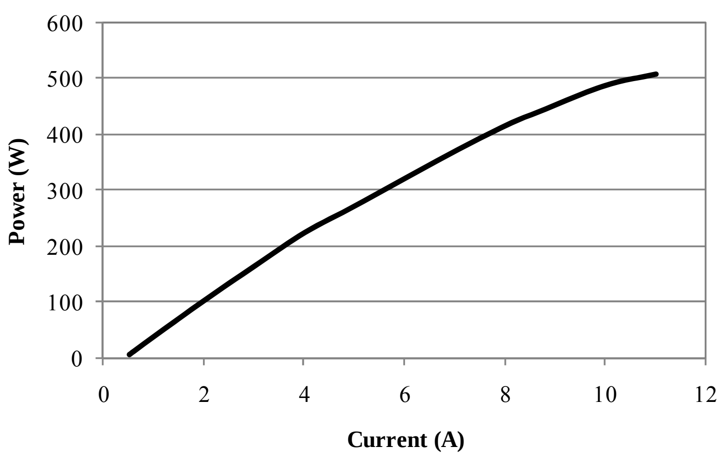

Fig. 9*: LI curve from a 7:1 fused fiber combiner demonstrating in excess of 500 W of optical power coupled into a 220 µm, 0.22 NA fiber.*

6. CONCLUSIONS

We have demonstrated what we believe to be the highest brightness single wavelength fiber coupled diode laser package to date, at >21 MW/cm^2-str. As of this writing, we are still actively developing this technology, and planning for a product release in 2009. We expect to improve the overall O-O efficiency to > 85% by improving the fiber coupling efficiency and reducing P-mux losses. In the future, as higher power chips become available, power could be scaled even higher. For example, if 15W per chip becomes available, we could scale the power of this package to 180 W. A 105 µm, 0.22 NA package with similar technology could reach up to 360 W in a single wavelength. This corresponds to brightness levels of 29 MW/cm^2-str and 27 MW/cm^2-str respectively. Such brightness levels would bring diode lasers into direct competition with diode-pumped solid-state lasers. Additionally, we believe these results to be of great interest to the fiber laser and direct diode materials processing industries.

ACKNOWLEDGEMENTS

This work was partially funded under NASA SBIR contract NNG07CA11C.

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