Advancements in laser diode chip and packaging technologies for application in kW-class fiber laser pumping

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ABSTRACT

A new 100μm aperture, 920nm laser diode chip was developed to improve fiber coupling efficiency and reliability. These chips have been assembled into single-emitter and multi-emitter packages with 105μm diameter fiber-coupled output. The single-emitter package is rated for 12W operation, while the multi-emitter package is rated at 140W. Power conversion efficiency is 50%. Over one year of accelerated active life testing has been completed along with a suite of passive, environmental qualification tests. These pumps have been integrated into 2kW, 4kW, and 6kW fiber laser engines that demonstrate excellent brightness, efficiency, and sheet metal cutting quality and speed.

Keywords: laser diode, fiber-coupled, multi-emitter package, reliability, high-brightness, pump laser, fiber laser, sheet metal cutting

1. INTRODUCTION

Laser based material processing is the largest market for lasers outside of communications.[1] Applications in the “macro” materials processing market, with laser power in the range of 1kW and greater, include metal cutting, welding, brazing, and marking. Within this segment, fiber lasers are rapidly replacing traditional laser sources such as CO_2 and diode-pumped solid state rod and disk lasers due to their superior beam quality, efficiency, and operating cost. The laser diode pump is an important component of the fiber laser system that drives overall performance, reliability, and product cost. Most fiber laser systems today utilize fiber-coupled diode lasers to realize a monolithic (fully fused) fiber architecture and its inherent stability and reliability.

In 2008, we introduced a new laser diode chip and single-emitter based packaging platform that provided 10W of optical power at 915nm lasing wavelength from a 105μm diameter, 0.22NA fiber with 95% of the power confined to less than 0.12NA.[2] The product characteristics included compact size, typical ex-fiber electrical-to-optical power conversion efficiency (PCE) of 50%, and low product sales price per optical power, i.e. low “dollars per Watt” ($/W).

In 2011, we demonstrated a new multi-emitter pump platform utilizing the same laser diode chip, but providing 100W of optical power from the same 105μm diameter, 0.22NA fiber.[3] This increase in power was accomplished via spatial stacking of the multiple 1μm x 100μm laser diode apertures, polarization combining two stacks, and focusing the resultant beam into the optical fiber. At 10A operating current, typical ex-fiber power was 100W and the PCE was 45%.

Here we introduce an improved laser diode chip that has high reliability at higher output power. The single-emitter fiber-coupled platform now provides 12W. The multi-emitter platform has been refined for higher coupling efficiency, power, and brightness, and now supports up to 140W. Finally, Amada and JDSU have integrated these pumps into a fiber laser with high efficiency, enhanced reliability, and low beam parameter product (BPP) at 2.1, 4.2, and 6.3kW output powers. Progress in each area is detailed in the following sections along with the resulting improvements in metal cutting speed and quality.

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2. LASER DIODE CHIP

2.1 JDSU wafer fab

The laser diode chips described here were developed, grown, and processed in our wafer fabrication facility in San Jose, California. This site produces all of JDSU's edge emitter and vertical cavity surface emitting lasers used in industrial, commercial, and telecommunications applications. A subset of these lasers are so called "high-power" GaAs-based edge-emitting lasers, and these serve three primary markets: multi-mode 9XXnm lasers for fiber laser pumping as described here, single-mode 980nm lasers for erbium-doped fiber amplifier pumping, and 800-1000nm single-mode and multi-mode lasers for consumer applications such as gesture recognition / 3D imaging. Since the basic technology is similar for these three laser types there is tremendous synergy and cost leverage to having these lines collocated. In calendar year 2013, several 10s of MW of optical power from these product lines was shipped to our customers.

All production is based on 3-inch GaAs substrates and metal organic chemical vapor deposition (MOCVD) epitaxial growth technology. An example of the manufacturing performance stability versus time for a typical product line over a six month period is shown in Fig. 1, where the normalized average operating current per wafer is plotted versus sequential growth time. The standard deviation is 1.1%.

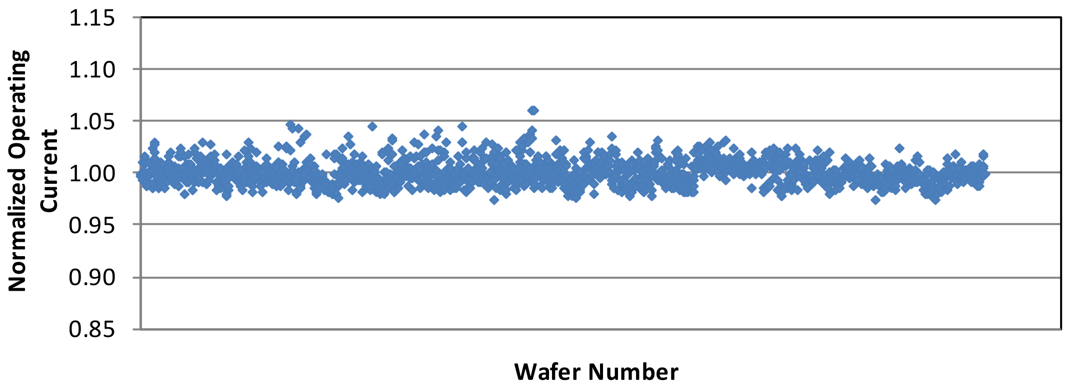


Figure 1. Operating current, normalized to the average, versus wafer growth number over a six month period. The standard deviation is 1.1%.

2.2 New chip design and performance

The latest generation, broad-area multi-mode chip is constructed in similar fashion to previous generations.[2] It utilizes a separate confinement InGaAs/AlGaAs quantum well structure with an aperture of ~100µm, cavity length of 4.1mm, and internal loss of <1cm^{-1}. The quantum well indium composition is varied to adjust lasing wavelength between 910 to 980nm. The chip is bonded to an expansion-matched ceramic submount with AuSn solder and clamped to a copper carrier for test and burn-in. Figure 2 shows a comparison of the previous generation chip to the new chip at the chip-on-submount (COS) level. Less rollover is evident, and over 20W of CW power is achieved at 25°C. The peak power conversion efficiency (PCE) is greater than 60%.

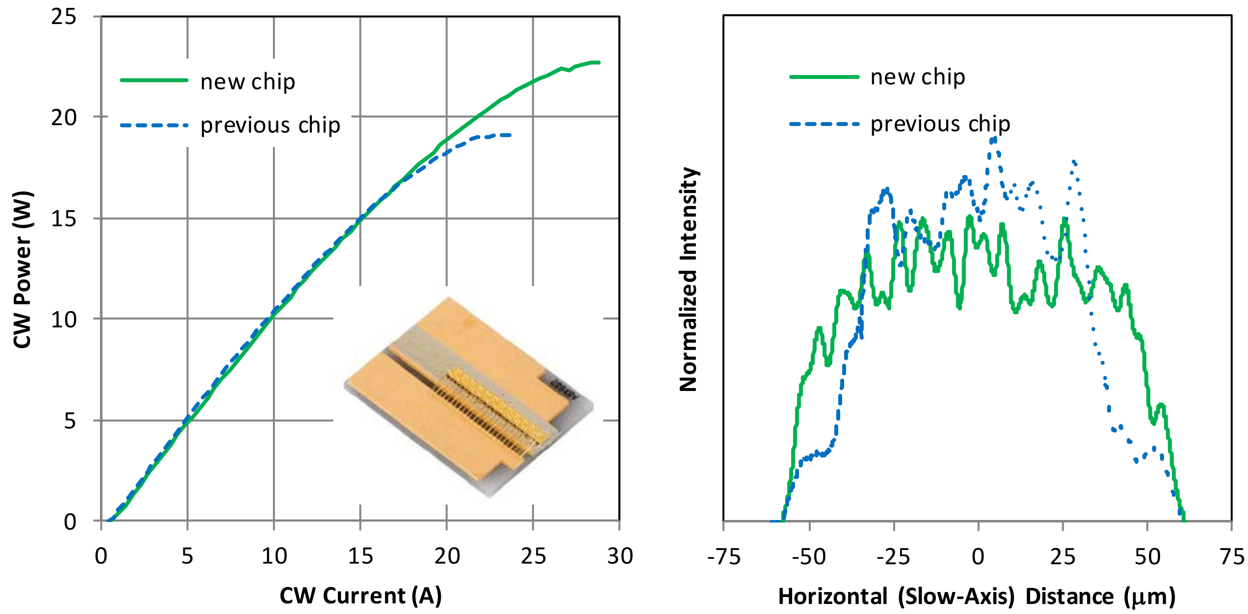


Figure 2. Left side: CW power versus drive current at 25°C for the new chip compared to the previous generation. Both chips have 4.1mm cavity length. Right side: near field images of the intensity at the front facet at 12W, 25°C. The new chip has better uniformity and lower peaks, which should lead to better facet reliability.

While the chip cavity length was maintained at 4.1mm, the same as the previous generation, the near field and far field emission patterns have been improved through optimization of the lateral index guiding step, lateral gain profile, and transverse (epitaxial direction) mode design. As shown in Fig. 2, these improvements result in a more uniform near field pattern, with fewer high-intensity spikes, which we believe leads to better long-term facet reliability.

2.3 Chip-on-submount multi-cell reliability life test

A highly-accelerated, multi-cell life test of the new chip was performed to create a reliability model and assess the long-term failure rate. A total of 240 lasers were built from a matrix of six wafers comprised of: five growth runs, two growth reactors, and four process runs. They were assembled and burned-in at a common condition. The lasers were then distributed across seven different operating conditions at constant current and temperature. Drive current ranged from 13.8-19A, optical power ranged from 10.3-15.6W, and diode junction temperature ranged from 74-129ºC. See Table 1 for details on the test conditions and number of units in each cell.

Table 1. Multi-cell life test conditions. 240 lasers were distributed amongst seven cells. 24 failures have been observed to date.

Cell	Case Temp (°C)	Current (A)	Power (W)	Number of Units	Time (h)	Number Failures
cell 1	35	13.8	12.6	64	7,701	4
cell 2	35	15	13.4	48	8,049	3
cell 3	35	17	14.6	24	8,712	2
cell 4	35	19	15.6	24	8,383	11
cell 5	50	15	12.6	24	8,334	1
cell 6	60	17	12.6	24	8,197	2
cell 7	75	15	10.3	32	8,037	1
total				240		24

The life test is ongoing and has accumulated over 8,000 hours of active testing to date. Example drift plots showing approximate optical power versus time for cell 3 and cell 5 are shown in Fig. 3. Note that the failures are abrupt in nature, typically without a precursor, and result in near zero optical power. The failed diode retains its pre-failure current-voltage characteristic within a few hundredths of a volt, and neither becomes an open circuit nor short circuit. Table 1 lists the number of failures per cell condition.

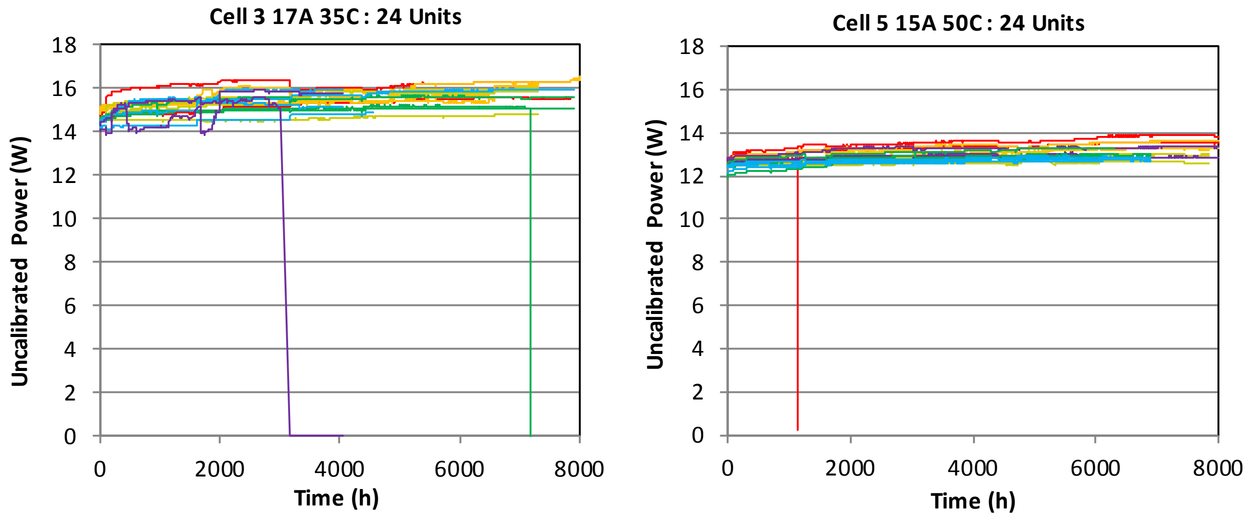


Figure 3. Approximate optical power versus time for Cell 3 and Cell 5 of the chip-on-submount life test. From these 48 units, 3 sudden failures were observed.

After approximately 8,000 hours of testing, the test was suspended and each laser underwent a bench top test with calibrated power meter. The operating current for 12W output power at the 8,000 hour point was compared to the start of the test. As shown in Fig. 4, on average there is a slight improvement (reduction) in current required for 12W, and in all cases only a few percent difference was measured. Therefore, we expect that there will be no laser wear out or gradual degradation at any time during deployment of the chip.

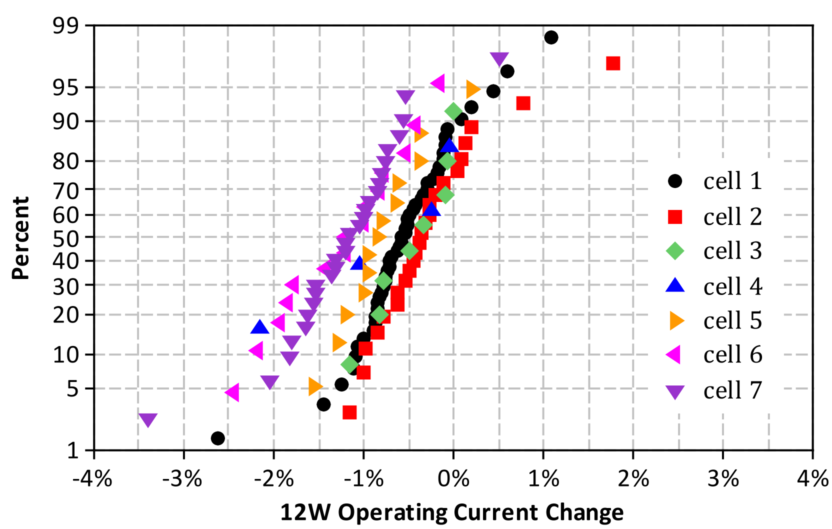


Figure 4. Change in operating current at 12W after 8,000 hours of life testing compared to beginning of test. On average, there is a slight improvement (reduction) in current for all cells.

There are only 24 diodes, or 10% of the tested population, that have failed across the seven cells. This makes the extraction of a reliability model difficult and we expect that the model parameters may change somewhat over time.

Nevertheless, we use the maximum likelihood method to fit a Weibull model with acceleration factors based on diode junction temperature and optical power. Cumulative failures F(t) at time, t, is given by equation (1), with characteristic scale parameter, η, given by equation (2).

$$F(t) = 1 - \exp\left(-\left(\frac{t}{\eta}\right)^{\beta}\right) \quad (1)$$

$$\eta = C \exp\left(\frac{E_a}{k_B T_j}\right) \Big/ P^n \quad (2)$$

Activation energy was fixed to E_a = 0.45eV as in prior models, and laser diode junction temperature, T_j, is calculated from thermal resistance and dissipated power. Extracted shape parameter β = 1.7, and power acceleration factor n = 6.5. The resulting scale parameter at 12W, 25°C is η = 570,000 hours, and cumulative failures from the model at 20,000 hours is 0.3%. Three early failures fell outside of the model and were removed. These can be treated as infants and eliminated with a longer burn-in. A use level plot of the failures and Weibull fit is shown in Fig. 5.

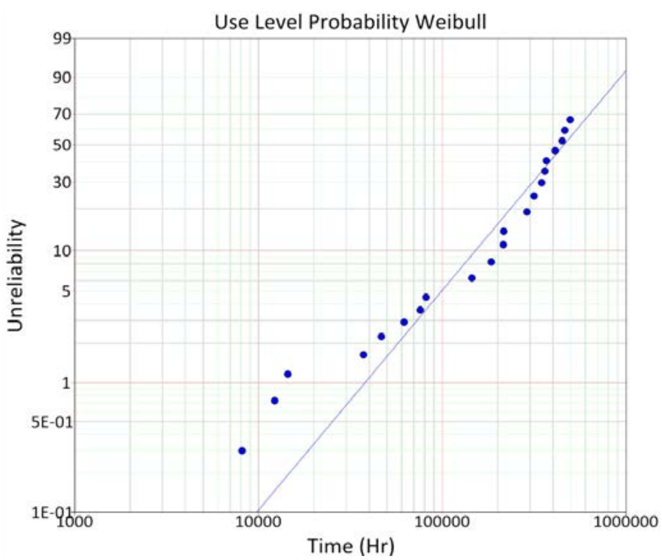


Figure 5. Use level Weibull plot of cumulative failures versus time at 12W, 25°C case temperature.

3. SINGLE-EMITTER FIBER-COUPLED PACKAGE

3.1 Design and performance

For applications where modest power and brightness levels are required, a single chip may be assembled into a fiber-coupled package. This architecture allows the lowest $/W pricing relative to multi-emitter packages. A picture of the single-emitter package is shown as the inset of Fig. 6. This package has been in continuous production since 2008, with over one million units deployed in applications such as fiber laser pumping, telecommunications amplification, printing, and medical with excellent field reliability. Performance of the new chip in this package at 35°C case temperature is shown in Fig. 6. The new product is rated at ex-fiber power of 12W CW from 105µm / 0.22NA fiber. Over 95% of the power is typically contained within 0.15NA.

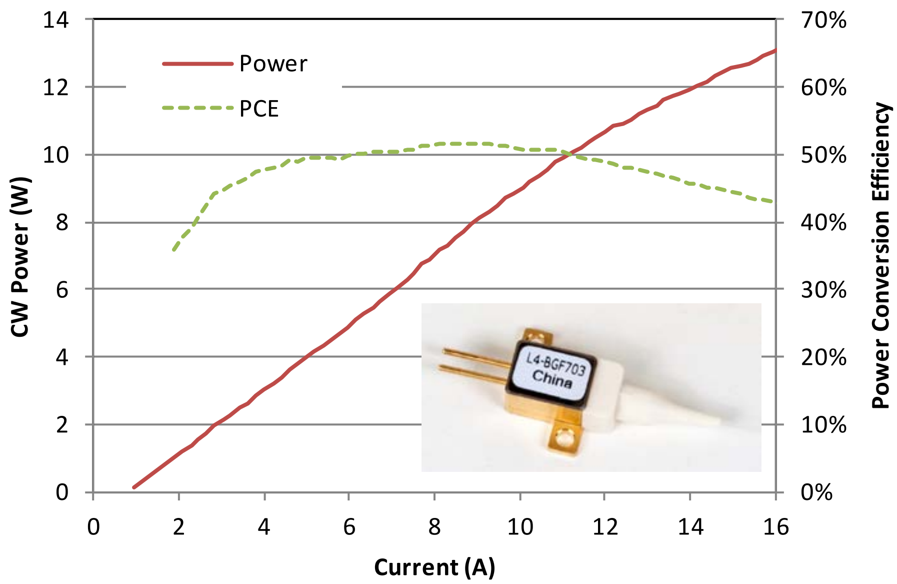


Figure 6. Power versus current at 35°C case temperature for the new 12W rated single-emitter package.

3.2 Single-emitter pump qualification tests

A significant number of accelerated device hours have been collected over the years on this single-emitter platform from initial and periodic qualification tests as well as ongoing reliability testing. As shown in Table 2, over 3.9 million raw device-hours from active and passive stress tests on over 1,300 units have been accumulated. Assuming a package activation energy of E_a = 0.53eV and typical field package case temperature of 35°C, this corresponds to 9 million use device-hours without a single package failure, or about 100 FIT (device limited).

Table 2. Summary of accelerated stress tests on over 1,300 single-emitter packages. There have been no package failures.

Conditions	Minumim Test Time (h)	Maximum Test Time (h)	Raw Test Device-Hours	Package Failures	Accelerated Device-Hours
Active: 12A, 35°C	7,820	13,504	2,989,886	0	1,517,832
Active: 12A, 70°C	4,488	12,206	390,417	0	2,936,583
Active: 15A, 55°C	8,546	8,546	72,958	0	243,626
Damp Heat: 50°C/85%RH	7,850	7,850	102,050	0	255,641
Damp Heat: 40°C/90%RH	5,000	7,000	144,000	0	197,492
Damp Heat: 85°C/85%RH	1,000	1,000	12,000	0	189,935
Dry Storage: 85°C	7,000	7,850	233,150	0	3,690,278
Total			3,944,461	0	9,031,387

4. MULTI-EMITTER FIBER-COUPLED PACKAGE

4.1 Design and performance

For applications where high power and brightness are desired, multiple chips are assembled into a single fiber-coupled package, while maintaining excellent $/W. The newly developed chip has been incorporated into the multi-emitter package pictured in the inset of Fig. 7. The chips are spatially stacked in the vertical direction in two rows, polarization combined, and focused into the output fiber. It is rated at 140W CW output power from 106µm / 0.22NA fiber with over 95% of the power contained within 0.15NA. Power conversion efficiency is nearly 50% at 140W.

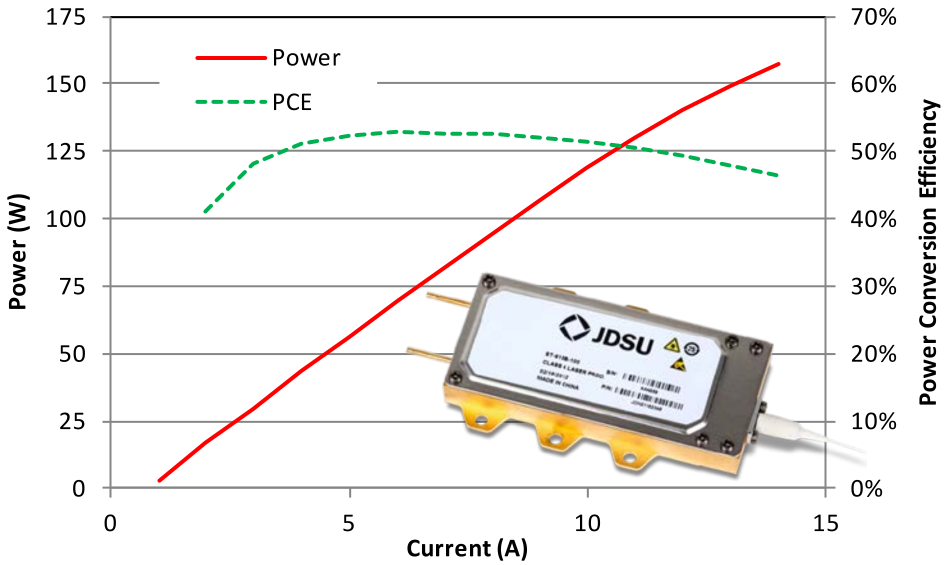


Figure 7. Optical power versus drive current at 35°C case temperature for the multi-emitter, fiber-coupled package. The laser is rated at 140W and achieves nearly 50% power conversion efficiency at the rated power.

This platform has been in continuous production throughout 2013 and has shown excellent process stability. Figure 8 shows the distribution of power measured at 10A, with typical power about 120W. This distribution represents the total variation in ex-facet chip power/efficiency, polarization-combination, and optical coupling efficiency.

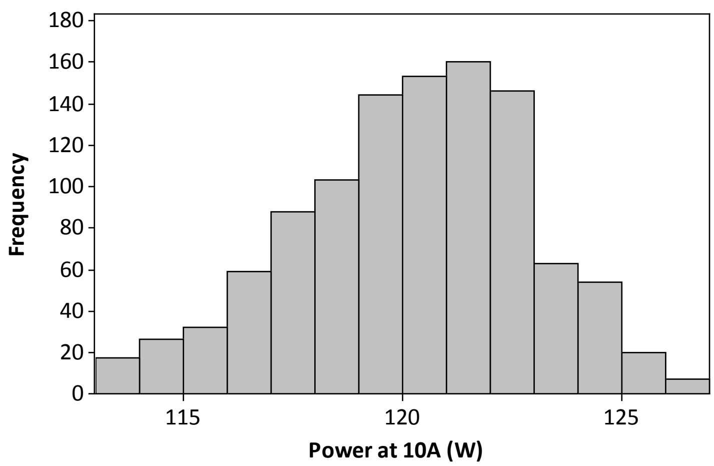


Figure 8. Optical power reading at 10A from most recent 1,000 units assembled. Typical optical power is about 120W.

4.2 Package qualification tests (passive)

In order to assess the stability and robustness of the package to environmental conditions, a series of accelerated stress tests were performed. Test conditions were leveraged from the Telcordia GR468 standard for telecommunications components. Optical power was measured at 10A (approximately 120W) at the beginning of each test and at periodic intervals during the passive testing. Figure 9 shows the results on six units each for high temperature storage at 85°C for 4,000h, and low temperature storage at -40°C for 72h. Figure 10 shows the results from damp heat tests on 24 units at 45°C / 50% relative humidity (RH) for 2,000h, and on 12 units at 45°C / 90% RH for 1,000h. Figure 11 shows the results for 12 units of temperature cycling from -10°C to 65°C for 100 cycles, and 4 units of 500G mechanical shock and 20G vibration. In all cases, there were no failures and only small changes in optical power.

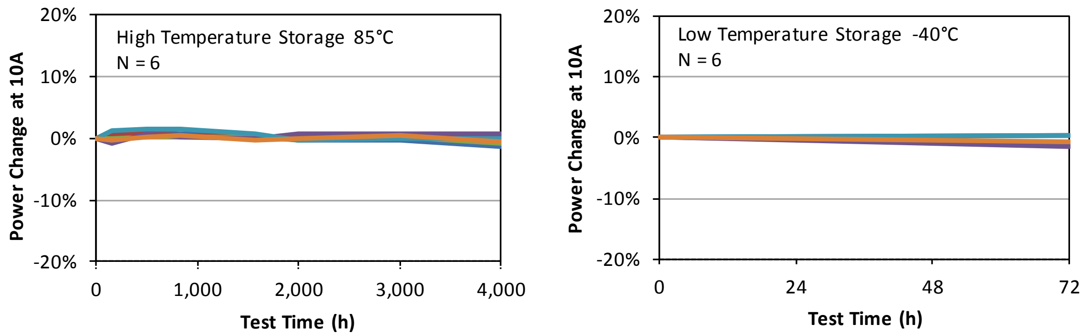


Figure 9. Left side: high temperature storage on 6 units at 85°C. Right side: low temperature storage on 6 units at -40°C.

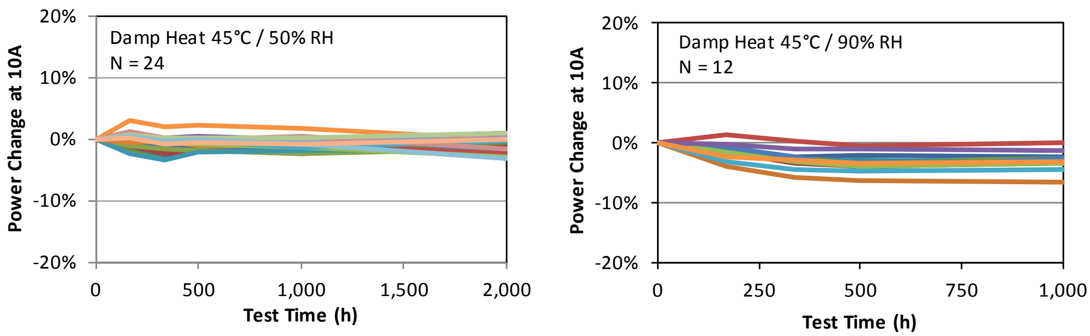


Figure 10. Left side: damp heat on 24 units 45°C / 50% RH. Right side: damp heat on 12 units 45°C / 90% RH.

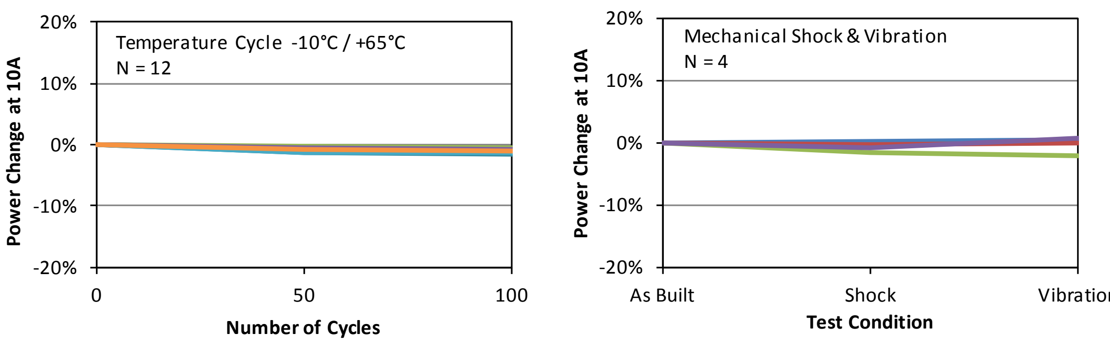


Figure 11. Left side: temperature cycling on 12 units from -10°C to +65°C. Right side: mechanical shock (500G, 1ms, 5 times/axis), and vibration (20G, 20-2000 Hz, 4 min/cycle, 4cycle/axis) on 4 units.

4.3 Multi-emitter pump life tests (active)

In addition to the passive tests listed above, active (laser diode on) life testing has been performed. Tests were carried out at several optical powers and case temperatures, as summarized in Table 3. Tests are ongoing and between 8,200 and 8,900 hours have been accumulated to date on 48 units in CW mode, with individual ex-fiber output powers ranging from 125-166W, and case temperatures ranging from 33-40°C. There have been no package failures.

Table 3. Average optical power and case temperature for 48 multi-emitter packages distributed amongst five cells. No package failures have been observed after 8,200 to 8,900 hours of CW testing.

Power (W)	Case Temp (°C)	Number of Units	Package Failures
130	33	16	0
141	34	15	0
144	38	10	0
156	36	5	0
164	40	2	0
total		48	0

An additional six units have been operated for over 8,200 hours in hard-pulse mode to assess robustness to thermal and optical cycling. These packages were pulsed between 130W and 0W at 63% duty cycle on a 20s period. This amounts to over 1.5 million cycles per unit without failure.

Example optical power versus time drift plots for three units from these active life tests are shown in Fig. 12. Several chip failures are apparent in the plots, but the stability of the overall power remains excellent after individual chip failure. In an ensemble application, where multiple, multi-emitter packages are combined to provide several kilowatts of pump power, this allows independence of failure amongst hundreds of individual chips, thereby enabling graceful, predictable degradation of the overall fiber laser system. Drive current may be periodically or continuously increased to maintain constant total optical power over the full deployment life time.

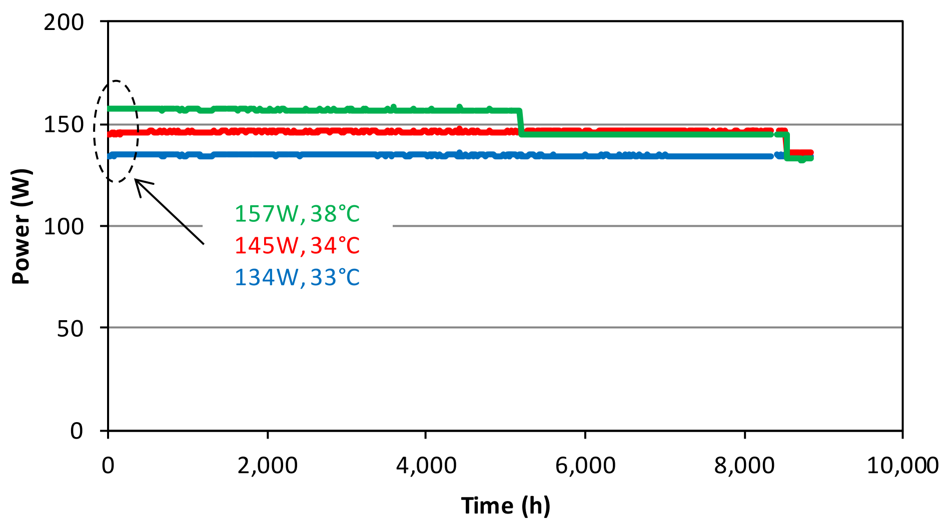


Figure 12. Example power versus time drift plots of three fiber-coupled packages in the accelerated life test. One pump (plotted in green) shows evidence of two chip failures, one pump (plotted in red) shows one chip failure, while one pump (plotted in blue) does not show any chip failures.

Fiber coupling stability through these active tests is demonstrated in Fig. 13. Individual chip failures have been removed and the associated drop in power normalized such that the alignment stability can be assessed. The mean change in coupling efficiency based on these in-situ power measurements is estimated at -0.7%, although this needs to be validated in the future with calibrated bench top tests. Based on the calibrated, high temperature storage results shown in Fig. 9, we expect negligible power drift under use conditions.

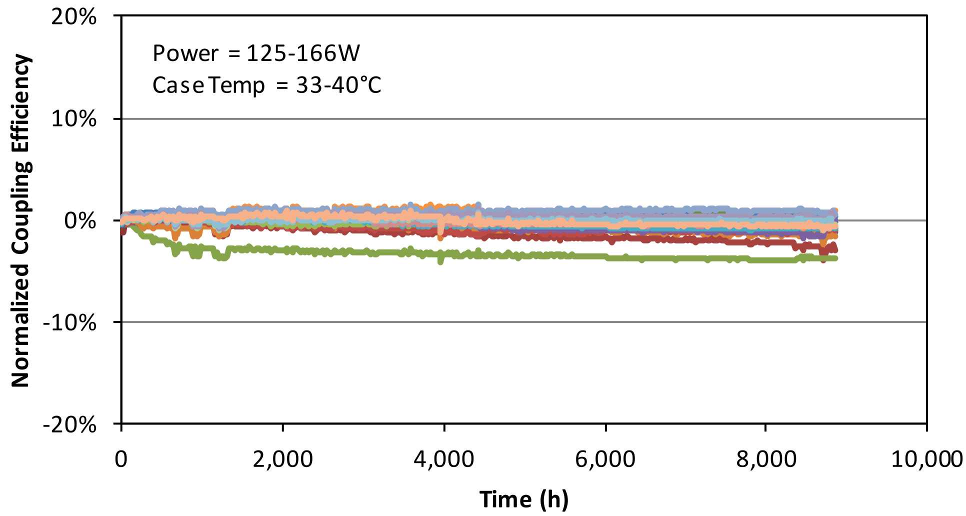


Figure 13. Normalized coupling efficiency versus time for the accelerated active tests. The power drop from individual chip failures has been removed to quantify change coupling stability.

5. FIBER LASER AND CUTTING RESULTS

5.1 Fiber laser performance

The high-brightness, multi-emitter pump described above has been integrated into a fiber laser jointly developed by JDSU and Amada. The pump output fibers are fusion combined and spliced to end-pump a 2.1kW fiber laser module building block. The module, with dimensions of 433mm x 153mm x 650mm, is shown in Fig. 14. Typical electrical-to-optical efficiency is 35%, rise and fall times are 16µs, and the beam parameter product (BPP) from the feeding fiber is 0.8mm-mrad.

The 2.1kW module may be used stand alone, or may be combined with additional modules for higher power. Using a 3:1 signal combiner, 4.2kW or 6.3kW fiber laser engines are realized. The resulting BPP for these higher power engines is 2.3mm-mrad. Fiber laser power versus laser diode pump current for one, two, and three module fiber laser engines is shown in Fig. 14.

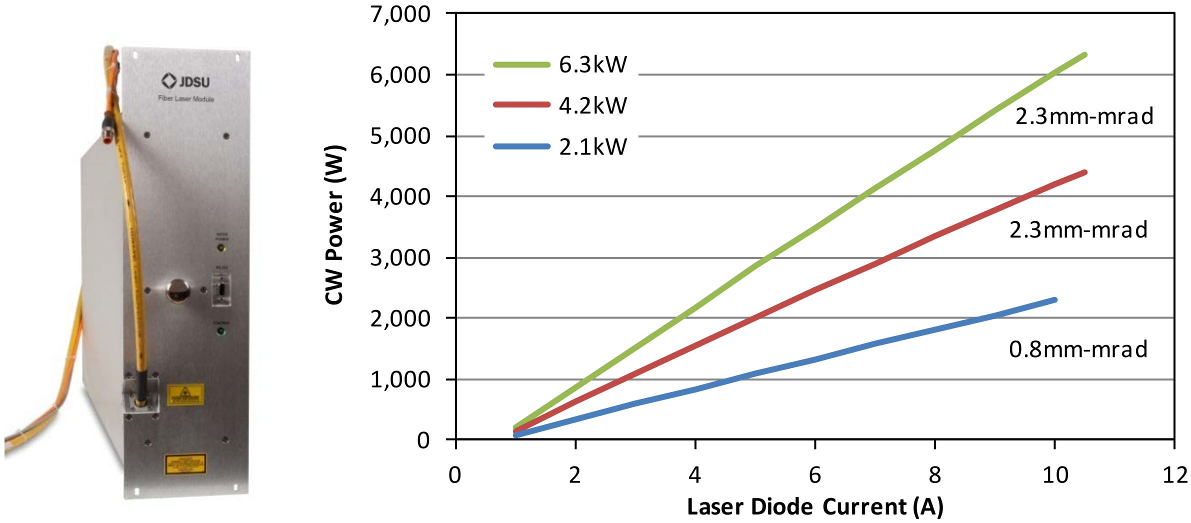


Figure 14. Left side: 2.1kW fiber laser module with dimensions 433mm x 153mm x 650mm. Right side: Fiber laser power versus pump diode current for 1-, 2-, and 3-module combined engines.

5.2 Amada fiber laser cutting system – ENSIS 3015 AJ

The fiber laser module has been incorporated into a new cutting system developed by Amada, the ENSIS 3015 AJ. The 2.1kW engine enclosure is shown in Fig. 15 and is integrated directly into the cutting tool, shown in Fig. 16. As shown in Fig. 15, the BPP from the processing head using 100µm process fiber is 2.2mm-mrad at 2kW. In addition, for the first time in the metal fabrication industry, the ENSIS system provides the flexibility to cut both thick and thin metals simply by changing the beam configuration electronically, dramatically saving time, costs and increasing productivity for metal manufacturers.

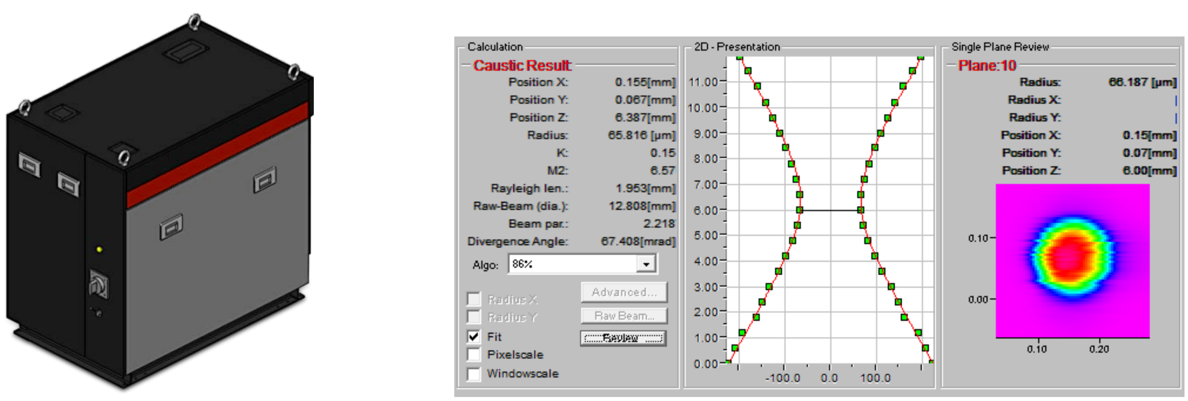


Figure 15. Left side: 2kW fiber laser engine enclosure. Right side: Beam quality measurement from processing head. BPP = 2.2mm-mrad at 2kW with 100µm core process fiber.

Figure 16. Amada fiber laser cutting system, ENSIS 3015 AJ, with integrated 2kW fiber laser.

5.3 Cutting performance

The cutting performance from this new 2kW tool is exceptional, and actually has comparable cutting performance to a 4kW CO_2 laser that requires twice the optical power, as shown in Fig. 17. To our knowledge, maximum cut thicknesses of 25mm for mild steel, and 14mm for stainless steel, have never before been demonstrated from a 2kW oscillator.

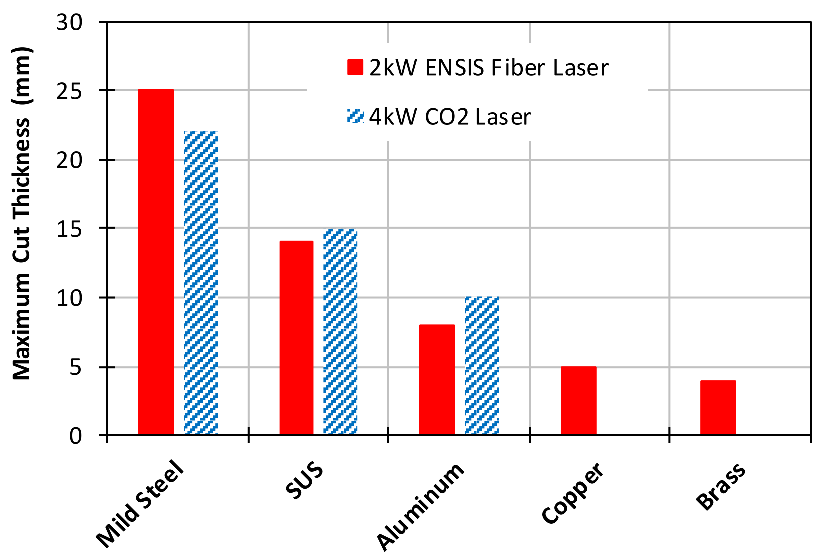


Figure 17. Maximum cut thicknesses for a variety of materials. Cutting performance from the ENSIS fiber laser system with only 2kW is comparable to a 4kW CO_2 laser.

Examples of cutting speed versus sheet thickness are shown in Fig. 18 for aluminum, stainless steel, and mild steel. For 1mm thick aluminum cutting, up to 40m/min. is possible at 2kW, and 75m/min. at 4kW. Figure 19 shows a cutting speed comparison for aluminum between the 4kW fiber laser system and a 4kW CO_2 laser reference system. A variety of cutting samples are shown in Fig. 20.

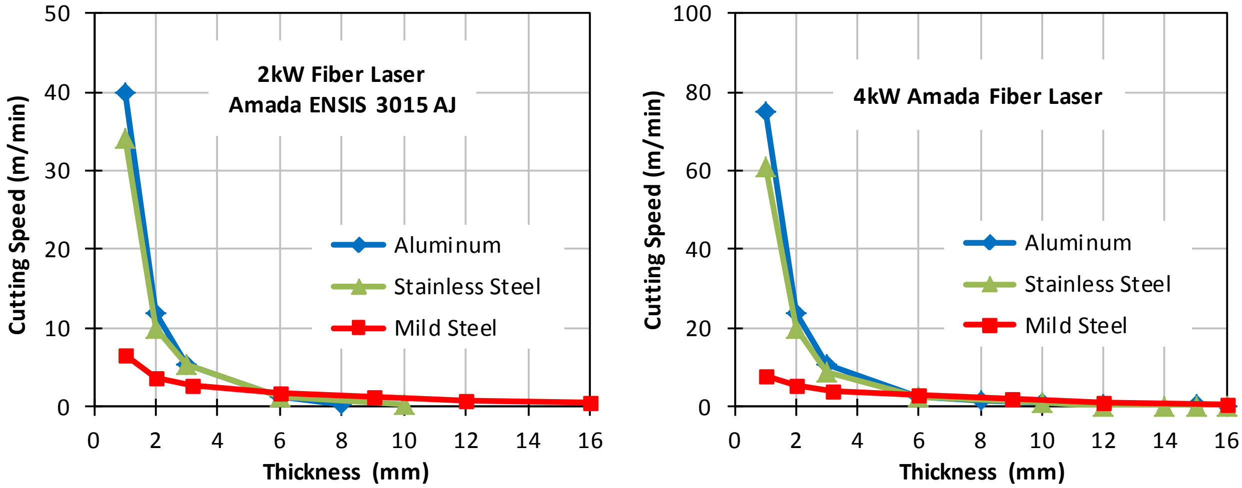


Figure 18. Cutting speed versus sheet thickness of aluminum, stainless steel and mild steel for the 2kW and 4kW fiber laser systems.

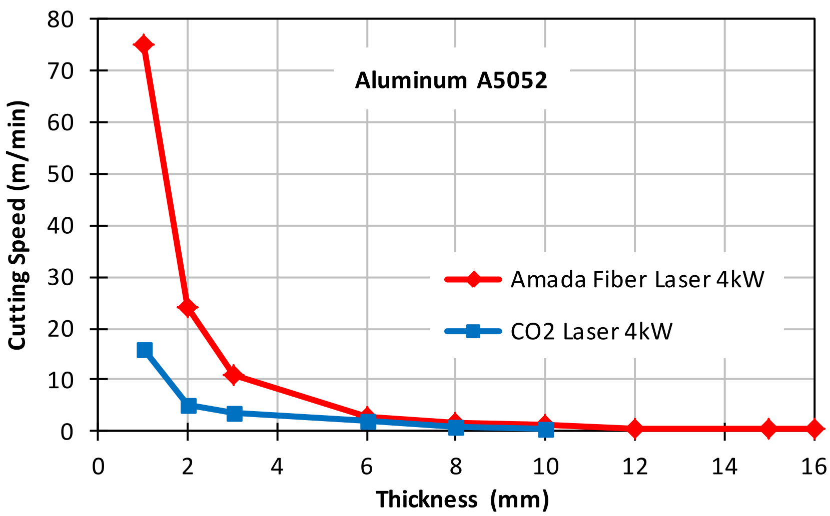
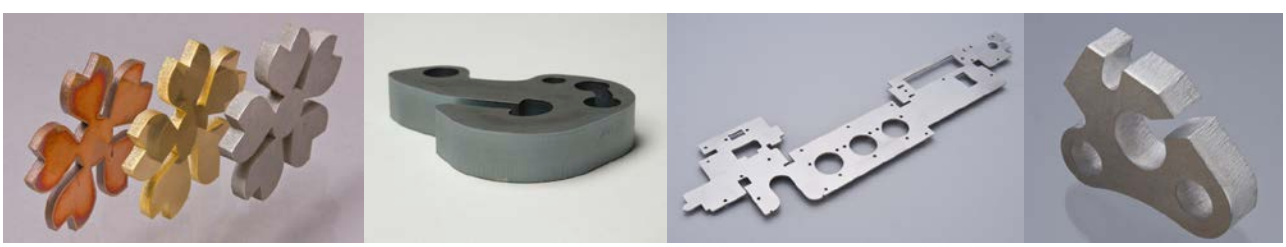


Figure 19. Cutting speed comparison for aluminum between the 4kW Amada fiber laser and a 4kW CO_2 laser.



Cu, Brass, Ti – 3mm thick | SS400 – 19mm thick | SUS304 – 2mm thick | A5052 – 16mm thick

Figure 20. Cutting examples from the Amada fiber laser cutting systems. 3mm thick copper, brass and titanium, 19mm thick structural steel, 2mm stainless steel, 16mm aluminum.

6. OUTLOOK AND CONCLUSIONS

We have developed an improved laser diode chip and incorporated it into single-emitter and multi-emitter fiber-coupled packages with ~105μm fiber diameter. Both pump packages have undergone extensive, highly-accelerated stress testing which demonstrate the environmental stability of the pumps and their suitability for deployment in industrial laser systems. Both package designs allow for graceful degradation of total pump power in ensemble-based systems. Based on overdriven active life testing, there appears to be ample headroom in the package designs to incorporate higher power chips in the future.

New 2kW, 4kW, and 6kW fiber lasers and cutting systems were developed based on the multi-emitter pump package. Excellent cutting speed, cutting quality, and maximum cutting material thickness have been realized.

REFERENCES

[1] Hausken, T., "The Worldwide Market for Lasers," 5th edition, Strategies Unlimited, Mountain View, CA, Chapter 3 (2012).

[2] Yalamanchili, P., et al., "High-power, high-efficiency fiber-coupled multimode laser-diode pump module (9XX nm) with high-reliability," Proc. SPIE 6876 (2008).

[3] Duesterberg, R., et al., "100W high-brightness multi-emitter laser pump," Proc. SPIE 7918 (2011).