KW-class Industrial Diode Lasers Comprised of Single Emitters

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ABSTRACT

Direct semiconductor diode laser-based systems have emerged as the preferred tool to address a wide range of material processing, solid-state and fiber laser pumping, and various military applications. We present an architectural framework and prototype results for kW-class laser tools based on single emitters that addresses a range of output powers (500W to multiple kW) and beam parameter products (20 to 100 mm-mrad) in a system with an operating efficiency near 50%. nLIGHT uses a variety of building blocks for these systems: a 100W, 105um, 0.14 NA pump module at 9xx nm; a 600W, 30 mm-mrad single wavelength, single polarization building block source; and a 140 W 20 mm-mrad low-cost module. The building block is selected to realize the brightness and cost targets necessary for the application. We also show how efficiency and reliability can be engineered to minimize operating and service costs while maximizing system up-time. Additionally we show the flexibility of this system by demonstrating systems at 8xx, 9xx, and 15xx nm. Finally, we investigate the diode reliability, FIT rate requirements, and package impact on system reliability.

Keywords: industrial laser diode, fiber coupled diode laser, high brightness.

1. INTRODUCTION

Direct semiconductor laser diode-based systems have emerged as the preferred tool for use in a wide range of material processing applications. Hardening, brazing, cladding, welding of metals, and plastic welding are all optimally performed by direct diode lasers. Technical advantages of using CW direct diode laser systems include the higher absorption of diode laser light as compared to YAG lasers, continuous tuning of the output power (0-100%), and the delivery of uniform light with tailored beam profiles. When coupled with efficiency advantages, reduced system cost, and virtually maintenance-free operation, these modules represent the devices with the lowest cost of ownership and the best value to the customer.

Key advantages of diode laser systems include:

> **Efficiency:** Direct diode laser systems do not suffer from the quantum defect and power conversion losses of fiber and solid-state lasers, resulting in higher laser system efficiency. Advances in micro-optics and beam combination aid in efficiently coupling diode light into the delivery fiber, with optical to optical efficiency values greater than 85%. Hence, the wall plug efficiency of diode laser systems is unsurpassed.
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> **Cost:** The primary cost of diode-based laser systems derives from the diode laser and corresponding micro-optics. Chip-on-submount devices and the corresponding micro optics can be manufactured inexpensively. Moreover, efficiently coupling the light from the diode laser into the fiber reduces the incremental loss due to unutilized light. By efficiently coupling the light from the diode laser into the fiber, the incremental loss due to unutilized light is reduced. Together, the high operating wall plug efficiency (>40%) coupled with low system costs result in a very low total cost of ownership.

Maintenance-free operation: In the past, industrial laser systems were notorious for their service requirements. Solid state and CO_2 lasers have stringent requirements for the lifetime of the lamps, mirrors, and gases. Micro-channel diode laser systems of the past also have tight specifications for the resistivity, cleanliness, and flow rates for the water used in the cooling system. Additionally, environmental conditions can have a significant detrimental impact on the reliability of diode laser systems in general. Organic residue, debris, and water condensation can contaminate the diodes, beam shaping optics, focusing optics, or the fiber, leading to heat absorption, blackening, and eventually system failure. The architectural choice of the diode laser system can preserve diode reliability as well as reduce, if not eliminate, the service requirements of the laser diodes. For instance, hermetically sealing a conductively cooled package can preserve the excellent laser diode reliability, virtually removing the need for service and maintenance.

nLIGHT's industrial laser systems based on single emitter technologies addresses all of these key points, resulting in systems that offer a low total cost of ownership and an optimal value in terms of price, operating cost and reliability.

2. EVOLUTION OF DIRECT DIODE LASER SYSTEMS

Through the years, diode lasers systems have evolved primarily to improve reliability, reduce service requirements, lower costs, and increase system performance. Here we show how the choice of the laser diode laser platform can have a significant effect on the reliability and performance of the industrial laser system.

The first high-power diode laser bars were based on micro-channel cooled laser bars. The available power and brightness of these devices has steadily increased over the years. These devices have demonstrated excellent high power performance [1,2] and promise continued gains in power and brightness. Through beam collimation, homogenization, and shaping, these systems have set the benchmark for high power laser diode systems. However, the cooling requirements on these systems are very stringent. The resistivity, cleanliness, flow rate and periods of stagnation of the water used to cool micro-channel cooled bars can have a significant impact on diode reliability and performance [3,4]. Corrosion and ionic deposition can also result in degradation in thermal resistance, increasing junction temperature, causing wavelength shift, and ultimately diode failure.

To overcome the drawbacks of micro-channel cooled bars, conductively cooled diode laser bars were next developed to provide the high power of laser bars, straightforward cooling requirements, and improved reliability. The increased thermal resistance of these systems forced the use of lower fill factor bars (typically 20-50%) with reduced diode brightness due to the higher operating junction temperature [2]. However, when the diodes are expansion matched to an interface layer and bonded with a hard solder, the devices can be operated reliability CW for many thousands of hours. In spite of the improved ease of system implementation, the overall brightness and cost of conductively cooled bars can be further improved by moving to single-emitter based architectures.

Single emitter laser diode systems represent the pinnacle of laser diode performance and reliability. Facet passivated, long cavity diode lasers can be operated at very high power levels with unparalleled brightness. Our low-cost chip-on-submount devices are individually screened to aggressive standards to remove substandard devices, resulting in device mean time to failure values measured in terms of hundreds of thousands of hours. These devices have an exceptionally high operating linear power density (in excess of 100 mW/um) due to the facet passivation while maintaining high operating efficiency (in excess of 60%) with very high brightness. The CoS design results in the absence of both thermal crosstalk and optical "smile," making superb fast axis collimation possible. The packaging strain of single emitters is significantly reduced due to the small chip size and the coefficient of thermal expansion (CTE) matching of the CoS design, allowing these devices to be operated in pulsed mode without degradation.

The advantages of single emitter-based industrial designs significantly improves industrial diode laser systems. The series connection of the diode lasers reduces the operating current enabling rapid power adjustments and pulsed operation while preserving diode reliability. The individually microlensed devices enable a highly efficient, straightforward optical design. An environmentally sealed box can remove the failure modes of condensation in the box as well as package induced failure (PIF). All of these features lead to systems with excellent efficiency, reliable performance, and low cost.

3. nLIGHT's APPROACH FOR INDUSTRIAL LASER SYSTEMS

For use in high brightness laser systems, nLIGHT is developing 9xx nm single emitter diode lasers with a 100um emitter aperture that is rated at 10 W at 976 nm. These devices have a peak efficiency of over 65%, have a 98% polarization purity for efficient polarization coupling, and operate at 10W with 60% efficiency. Each of nLIGHT's devices is hard soldered on expansion matched submounts and is individually screened by high power test, accelerated burn-in, and stringent visual inspection. A typical LIV curve is shown below in Figure 1.

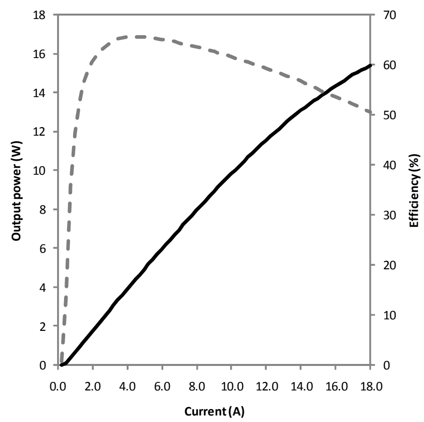

Figure 1. *LI and efficiency curves for a single emitter diode laser developed at nLIGHT. Such a device is rated at 10W of optical power with an operating efficiency of over 60% and a FIT rate of 1200 (90% confidence level).*

To assess the reliability of the new 3.8 mm cavity length diodes, a multi-cell life test has been ongoing for 3000 hrs to determine the temperature, current, and power acceleration factors, as well as the reliable operating conditions. A random failure acceleration model for sudden failures F accelerated by diode current I, optical output power P, and junction temperature T_j can be modeled as:

$$\mathbf{F(I, P, Tj)} \propto \left(\frac{I}{I_o}\right)^m \left(\frac{P}{P_o}\right)^n exp\left(\frac{-E_A}{k_B T_j}\right)$$

Using a thermal activation energy E_A = 0.45 eV, an exponent of current acceleration m=2.5, and an exponent of power acceleration of n=2.5, the random mean time to failure (MTTF) is estimated to be over 800,000 hrs with a 90% confidence level when operating at 10 W and with a 35ºC baseplate temperature. This MTTF value corresponds to a failure in time (FIT) rate at 90% confidence level of 1200 failures in a billion operation hours.

nLIGHT has utilized these single emitter packages to produce a patented line of fiber coupled multiple single emitter packages called Pearl™ [5, 6]. The product is based on high power broad area single emitters, free space combined in an elegant and inexpensive manner. 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.

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 fill factor is maximized for high brightness packages and reduced to loosen manufacturing tolerances for low brightness packages. After each emitter is collimated with fast axis collimation (FAC) and slow axis collimation (SAC) lens, rhombus prisms spatially combine columns of emitters. When desired, a polarization combiner can be used to increase the brightness of the system. Simple focusing lenses efficiently 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.

Based on the Pearl™ product line, nLIGHT has demonstrated a range of pump modules with excellent system brightness. Figure 2 shows a comparison of Pearl™ products with other commercially available diode pump modules in terms of brightness. The 2x8 and 2x7 boxes from the Pearl™ product line are used as a scalable building block for creating high power industrial laser systems. The performance of 120W, 200um and 100W, 100um, 0.15 NA products are shown below in Figure 3.

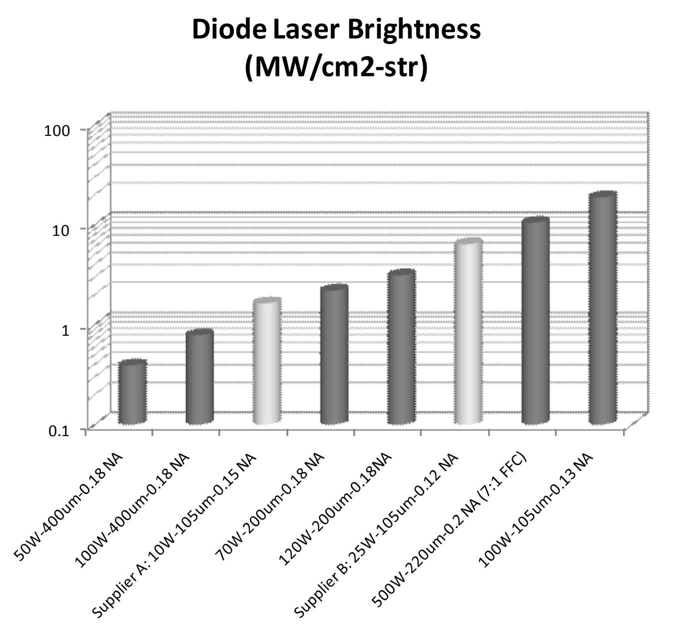

Figure 2. *Diode laser brightness (MW/cm2-str) for various diode laser pump modules. Brightness levels in excess of 18 MW/cm^2-str have been achieved using nLIGHT’s Pearl™ product line.*

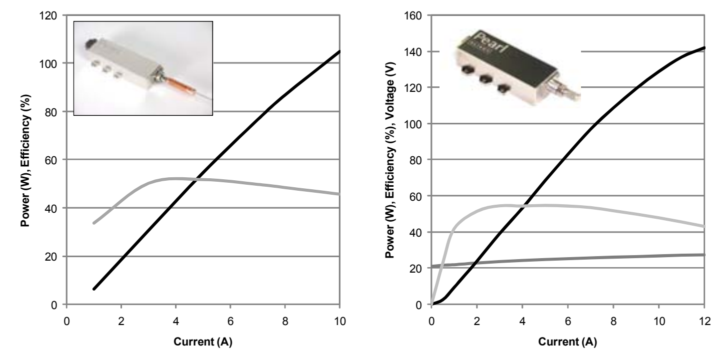

Figure 3. *(left) A Pearl module capable of coupling over 100W of optical power into a 0.15 NA, 105um fiber. (right) A Pearl module capable of coupling over 120W into a 200um, 0.2 NA fiber.*

To gauge the reliability of these packages, 9 modules were tested under a 10x acceleration condition (accelerated with high temperature and power operation). The measured FIT rate of the diode lasers in the package (1200 FIT) matched the FIT rate of individual diode lasers on a lifetest rack (measured FIT of 1150), demonstrating the absence of package induced failure (PIF). The lifetest performance for these devices is shown below in Fig. 4. With module failure being described as a 20% degradation in output power (or a corresponding 20% increase in bias current), with the given acceleration factor these diode lasers have the equivalent of over 75,000 hours of operation without a module failure. Similar packages are being operated under hard pulsed conditions, with 1 sec on and 1 sec off with a 20 ms rise and fall time. These devices have been tested for over 2500 hrs, without device failure.

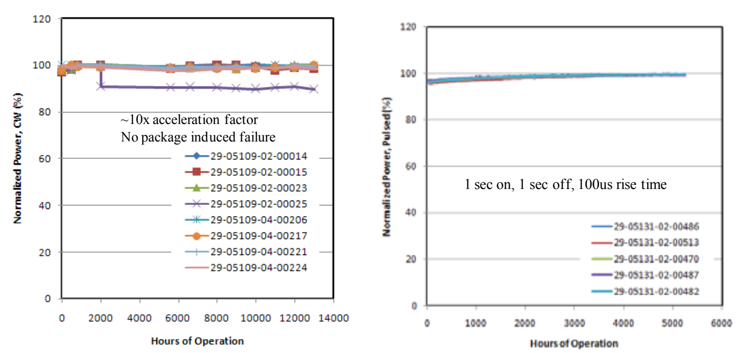

Figure 4. *(left) Reliability tests for 70W Pearl modules operating at 9xx nm. These devices are coupled into a 200um fiber at 0.2 NA. This lifetest is performed at an acceleration factor of ~10x, with a single emitter failure observed at ~2000 hours. These data represent over 140K of reliability under normal operating conditions. The absence of device degradation (right) Hard pulsed test (1 sec on, 1 sec off, 20 msec rise time) on Pearl modules as tested for over 5000 hours.*

In addition to lifetime testing, over 20 modules have been subjected to harsh environmental tests including 10g vibe (all three axes), 100g shock (all three axes), thermal cycling test (-40 to 85 ºC for 100 cycles), and high temperature storage (90 ºC storage for 100 hours). After thermal cycling the power drop as measured at the distal end of the fiber was ~2-3%. Shock testing resulted in a 2% power degradation and vibration testing resulted in a 2-3% power degradation. These results qualify the devices according to Mil-Std-883, indicating robust and rugged device design and manufacture.

4. HIGH BRIGHTNESS, SINGLE EMITTER LASER SYSTEM ENGINEERING

nLIGHT is introducing the first in a series of industrial laser systems based on single emitter technology. These devices utilize the free-space beam combination of several Pearl modules, resulting in a system that couples over 500W of optical power (single wavelength and single polarization) into a beam parameter product of 30 mm-mrad with over 40% system efficiency. A photograph of the system, as well as the performance of the module, is shown below in Fig. 5.

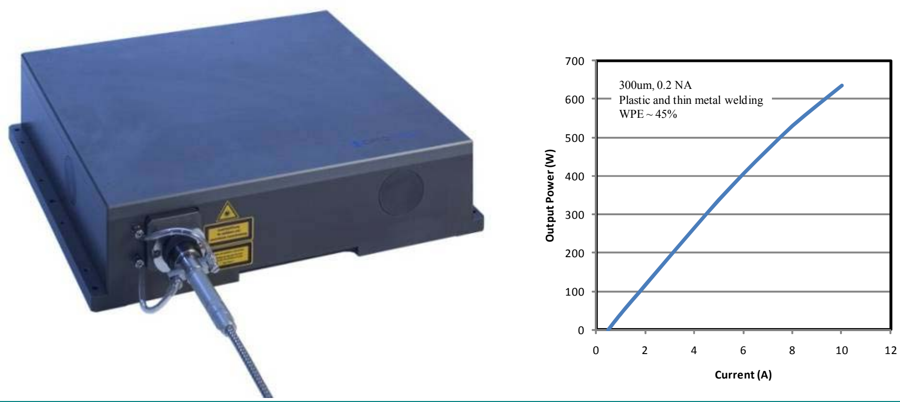

Figure 5. *(left) A picture of the single emitter-based system. The device utilizes a single polarization and wavelength to put over 500 W of output power into a 300um, 0.2 NA fiber. (right) The light versus current curve for the module.*

This laser module can also be used as a building block to achieve > 1KW of optical power. A prototype KW-class laser module is shown below in Fig. 6. This device couples over 1 KW of optical power into a 40 mm-mrad fiber.

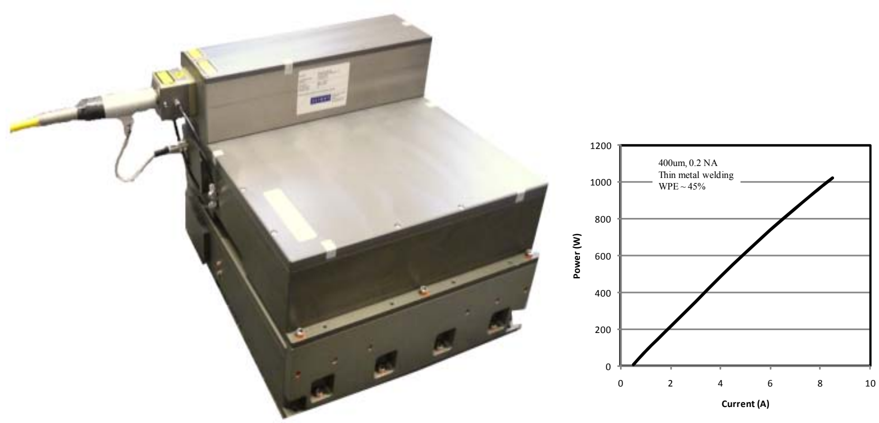

Figure 6. *(left) A KW-class laser diode system based on single emitters. The device utilizes wavelength beam combination to achieve over 1000 W of output power into a 400um, 0.2 NA fiber. (right) The light versus current curve for the module.*

Mechanical features include a hermetically sealed diode laser container to keep contaminants out of the system, robust fiber delivery with the ability to field-replace the fiber, and parallel cooling water flow to each Pearl module for excellent thermal matching. This module is also integrated with control and driver electronics to provide detailed status feedback to the customer and to provide the module with a robust and reliable power supply. The module is compatible with industry-standard fiber cables.

5. FIBER BUNDLE HIGH POWER LASER SYSTEMS

As an alternate to free-space beam combination, nLIGHT has developed the fiber bundle as an approach for scaling the power of industrial laser diode systems. By bundling the output fibers of high brightness fiber coupled laser diodes modules together, extremely high output power levels can be achieved while maintaining approximately 66% brightness conservation. A schematic illustration of the fiber bundle approach is shown below in Fig. 7. The proposed product space is shown below in Fig. 8.

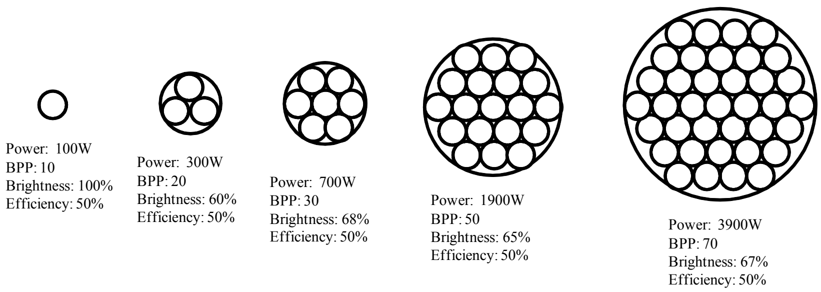

Figure 7. *An illustration of the power and BPP of 1, 3, 7, 19, and 39 element fiber bundles. As can be seen, about 65% of the brightness is preserved when using fiber bundles. The residual brightness loss can be attributed to the interstitial space between fibers, as well as the thickness of the cladding layers. Note that efficiency values of approximately 50% are achieved for all power levels, proving a method to scale power without losing efficiency.*

Brightness Preservation for Fiber Bundles												
Number of Elements	P16, 200um, 0.2 NA			P14, 200um, 0.1 NA			P14, 105um, 0.14 NA			P72, 200um, 0.2 NA		
	Power (W)	BPP (mm-mrad)	Brightness (MW/cm2-str)	Power (W)	BPP (mm-mrad)	Brightness (MW/cm2-str)	Power (W)	BPP (mm-mrad)	Brightness (MW/cm2-str)	Power (W)	BPP (mm-mrad)	Brightness (MW/cm2-str)
1	140	20	3.5	110	10	10.1	100	7.5	18.8	500	20	12.7
3	420	42	2.1	330	21	6.1	300	16	10.3	1500	42	7.6
7	980	60	2.4	770	30	6.9	700	22.5	11.5	3500	60	8.7
19	2660	100	2.3	2090	50	6.6	1900	37.5	10.7	9500	100	8.3
39	5460	140	2.4	4290	70	6.8	3900	52.5	11.0	19500	140	8.6

Figure 8. *The available product space in terms of power, BPP and brightness for fiber bundles laser modules. The flexibility of selecting the beam sources and the number of fibers in the bundle provides the highest flexibility in fiber coupled laser modules. A broad variety of products can be addressed with this approach.*

An initial prototype of the fiber bundle was demonstrated with 200um, 0.2 NA fiber coupled modules. 19 of these laser modules were coupled into a fiber bundle with a BPP of approximately 100 mm-mrad. The module achieved over 2 KW of output power at an efficiency of about 50%. These results are shown below in Fig. 9.

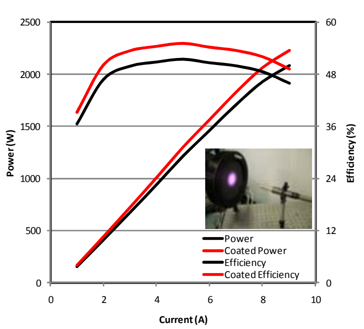

Figure 9. *A prototype demonstration of a 19 element fiber bundle that achieved over 2 KW of optical output power. The fiber bundle is packaged in a Trumph-compatible fiber with the individual fibers armor-jacketed.*

6. APPLICATIONS

These systems are ideally suited for plastics welding and thin metal welding. Figure 7 shows a variety of plastics welding products that have been developed using similar process parameters. Advantages of laser plastics welding include particulate free welding without abrasion, highest cost efficiency, low mechanical stress, contactless energy contribution, the highest seam quality (with gas proof welding possible), and the absence of required filling material or epoxy. For the welding of thin metals, reasonable weld speeds (>1.5 m/min) can be achieved, resulting in high quality butt and T-welds of zinc-coated steel that is 600um thick.

Figure 7. *(top and middle row) Examples of products enabled by laser plastics welding. These products are applicable in the consumer, to light industrial, and medical fields. (lower row) Butt and T-welding samples on zinc coated steel. High quality seams and uniform welds are possible with such laser systems.*

7. SUMMARY

Applications such as hardening, brazing, cladding, welding of metals, and plastic welding have used direct laser diodes as the source of choice based on performance, cost and reliability. nLIGHT's line of single emitter-based industrial laser diodes further improve these systems, providing unsurpassed reliability, high efficiency, and ultimately a low cost of ownership. The product architecture is based on telecom-grade single emitters, packages and techniques that maintain the reliability of the single emitters, and a product line that leverages platforms previously developed by nLIGHT. The resulting industrial laser systems demonstrate excellent reliability, high power, and high brightness.

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