High-Power Diode Lasers Operating Around 1500nm for Eyesafe Applications

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ABSTRACT

Er:YAG solid state lasers offer an “eye-safe” alternative to traditional Nd:YAG lasers for use in military and industrial applications such as range-finding, illumination, flash/scanning LADAR, and materials processing. These laser systems are largely based on diode pumped solid state lasers that are subsequently (and inefficiently) frequency-converted using optical parametric oscillators. Direct diode pumping of Er:YAG around 1.5 um offers the potential for greatly increased system efficiency, reduced system complexity/cost, and further power scalability. Such applications have been driving the development of high-power diode lasers around these wavelengths. For end-pumped rod and fiber applications requiring high brightness, nLIGHT has developed a flexible package format, based on scalable arrays of single-emitter diode lasers and efficiently coupled into a 400 um core fiber. In this format, a rated power of 25 W is reported for modules operating at 1.47 um, with a peak electrical to optical conversion efficiency of 38%. In centimeter-bar on copper micro-channel cooler format, maximum continuous wave power in excess of 100 W at room temperature and conversion efficiency of 50% at 6C are reported. Copper heat sink conductively-cooled bars show a peak electrical-to-optical efficiency of 43% with 40 W of maximum continuous wave output power. Also reviewed are recent reliability results at 1907-nm.

Keywords: Diode laser, semiconductor laser, eye-safe laser, laser pumping

1. BACKGROUND

To achieve the desired improvements in semiconductor diode lasers in peak power, special attention must be paid to designing the laser for peak electrical-to-optical (E/O) conversion efficiency. Improved E/O efficiency permits the diode laser to operate at higher output powers or a given active area temperature. As some of the solid-state media pumped by >14xx-nm diode lasers are three or quasi-four level lasers, peak power is vital to achieve population inversion. High E/O efficiency lasers will also operate cooler at a given output power reducing the need for costly and heavy cooling capability.

Traditionally, diode lasers operating at wavelengths of 14xx-nm and beyond have not been capable of demonstrating peak electrical-to-optical (E/O) efficiencies and useable peak powers comparable to lasers emitting around and below 1 m. There are three major loss mechanisms that contribute to reduced diode laser efficiency and power:

- Carrier loss through Auger recombination (comparable to up conversion in solid-state lasers)
- Optical losses
- Voltage drops

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Of these mechanisms, Auger recombination has the most deleterious effect on the performance of diode lasers emitting in excess of 1400-nm.

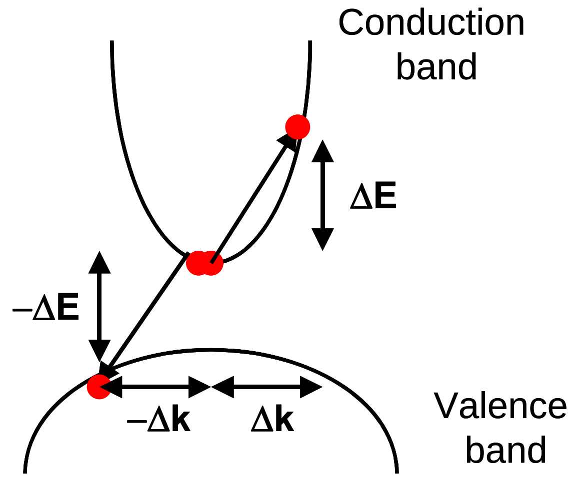

Figure 1 A schematic of the Auger process in semiconductors. An electron recombines with a hole acquiring momentum -ħk and releasing energy □E. Another electron acquires the energy □E and the momentum □k. The excited electron will dissipate its excess energy as heat, often escaping the active region. The Auger process results in a lost electron-hole pair, the loss of an electron and generates excess heat in or near the active region. This process is similar to that of upconversion in solid-state lasers.

Auger recombination is a many-body phenomenon where in a typical event an electron recombines with a hole, not by emitting a photon, but by transferring the energy to a third particle, usually an electron. The excited carrier will then, on average, recombine outside the active region, releasing its energy as heat. Auger then causes three problems, each detrimental to the functioning of the laser:

- An electron-hole pair is lost *without radiating a photon*
- Another electron typically escapes from the active region
- Heat is generated in or near the active region (increasing the likelihood of more Auger processes)

Therefore, minimizing Auger is one of the most important tasks in the proper design of high-power, high-efficiency lasers. While Auger recombination is present in all diode lasers it is most pronounced in the longer wavelengths of the InGaAsP-material system. Figure 1 shows the reason for this. The less energetic bandgap separation of the conduction and valence bands causes the bands to 'push apart' harder than in materials with larger bandgap energies. Auger recombination requires that both energy and momentum be conserved. The more sharply bent bands of the smaller bandgap material make it highly more probable that a set of particles can be found such that the Auger event can occur while conserving energy and particle momentum.

Aside from the bandgap of a material, the Auger effect is also dependent on a number of material parameters that include density of states and effective mass (closely related to the band bending described above). It is also dependent on various parameters that can be controlled through device design that include temperature and carrier density. With conventional InP-based material parameters and device designs, Auger related recombination losses can contribute ~ 10-20x more to loss than they do in shorter wavelength GaAs-based devices (Figure 2).

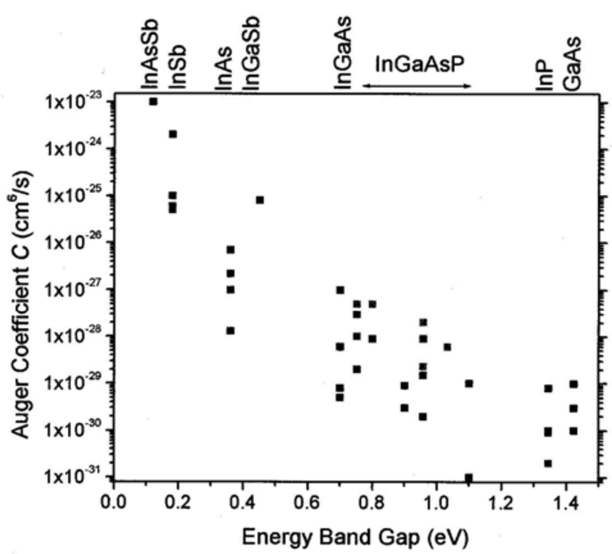

Figure 3.12: Auger coefficient C for direct-band-gap compound semiconductors at room temperature [47, 75, 77].

Figure 2. Auger coefficients as a function of bandgap energy. The Auger coefficient at the bandgap energies under consideration here, ~0.6-0.8eV, are two to three orders of magnitude greater than at the submicron wavelengths (1.25-1.5eV). This makes long wavelength diode lasers much more susceptible to increases in current densities and temperature. From J. Piprek, Semiconductor Optoelectronic Devices, Academic Press, 2003.

In other words, the Auger effect puts extremely stringent requirements on the design of InP-based laser diodes. While impossible to eliminate, the effects of Auger may be reduced with two design strategies:

- Device designs that make it more difficult for excited carriers to escape the active region of the laser.
- Device designs that lower carrier density in the quantum wells.

Due to the three-body nature of the process, Auger processes go to the third power of the carrier density, N^3. As the occupancy rates of the energy and momentum states of the crystal are strongly temperature dependent, so is the Auger process. Designing to minimize Auger events is the main criteria for high-power and highly efficient long wavelength diode lasers.

2. MICROCHANNEL AND CONDUCTIVELY -COOLED CM-BAR ARRAYS

Eyesafe laser systems wavelength range near 1.6 microns are typically based on frequency converted Nd:YAG lasers that are pumped with 808nm quasi-CW laser diode stacks. These laser systems have many disadvantages. Key among these disadvantages include high cost, driven by the short upper state lifetime of Nd:YAG, and their relatively large size and low efficiency which are driven by the need for an optical parametric oscillator (OPO) to perform the frequency conversion. The upper state lifetime of Er:YAG is between 5 and 10 milliseconds. This enables the Er:YAG crystal to be pumped for 25 to 50 times longer than an Nd:YAG crystal whose upper state lifetime is roughly 200 microseconds. This longer fluorescence lifetime enables the same amount of energy to be stored in the crystal with far less pump power. Further, because Er:YAG lases directly in the eyesafe wavelength range, there is no need for an OPO. This further reduces the required amount of pump power. Therefore, Er:YAG lasers pumped at 1470-nm offer an attractive alternative that improves electrical efficiency, lowers cost, and reduces package size [1].

A bar 1470-nm bar designed for high efficiency operation is shown in Figure 3, achieving 50% peak electrical-to-optical conversion efficiency with 6C cooling water [2]. Shown in Figure 4 is nLIGHT's state-of-the-art high-power laser diode bar capable of producing 100W at 20C on a water-cooled -channel cooler [2]. A bar 1470-nm bar designed for high efficiency operation A bar optimized for high efficiency, when mounted to a copper CS-mount (conductively cooled) demonstrates record high peak room temperature electrical-to-optical conversion efficiency (Figure 5) [2]. Both the 100W peak output power and the 42% room temperature conversion efficiency represent, to the best of our knowledge, represent significantly better performance than any laser bar operating in the 14xx-15xxnm region. As a result of this work, nLIGHT has made commercially available a 1470-nm laser bar rated at 50W when operated at 20C and 0.2 liters/minute water flow rate. Also available, is a conductively cooled 30W Cu CS-mount bar.

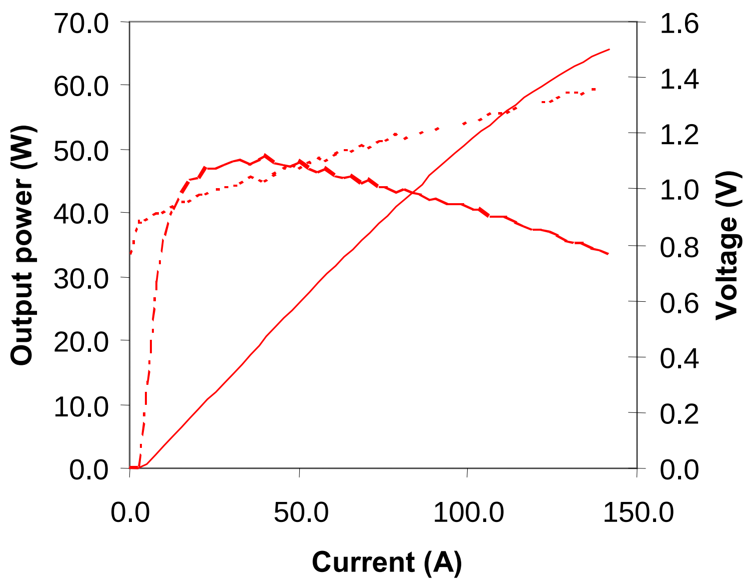

Figure 3: Power, voltage and efficiency v. current for a 1-cm 1470-nm diode laser bar operating at 6C water temperature. The bar has a 20% fill factor and a cavity length of 1-mm.

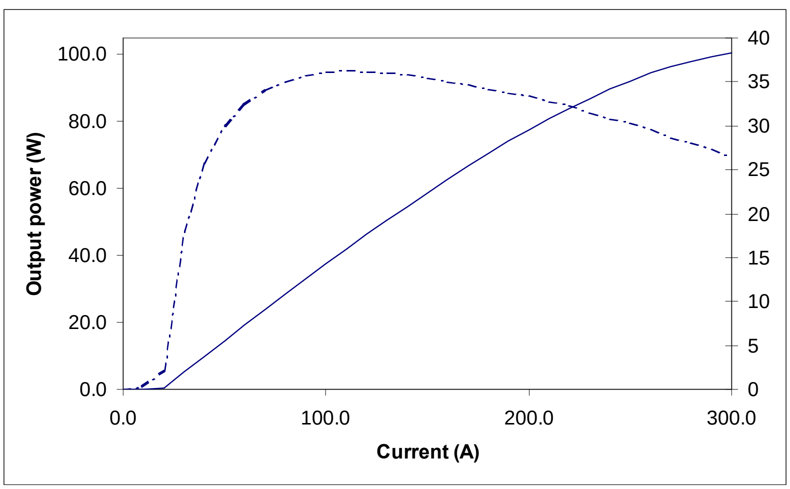

Figure 4. Under ARO contract W911NF04C-0137, for the development of high-power, high-efficiency, 1470nm diode laser bars, over 100W of CW output power was achieved with room temperature (20C) cooling water. This result represents to the best of our knowledge the best peak power performance for any laser bar operating in the 14xx-15xx region of operation, at any temperature and by a substantial margin.

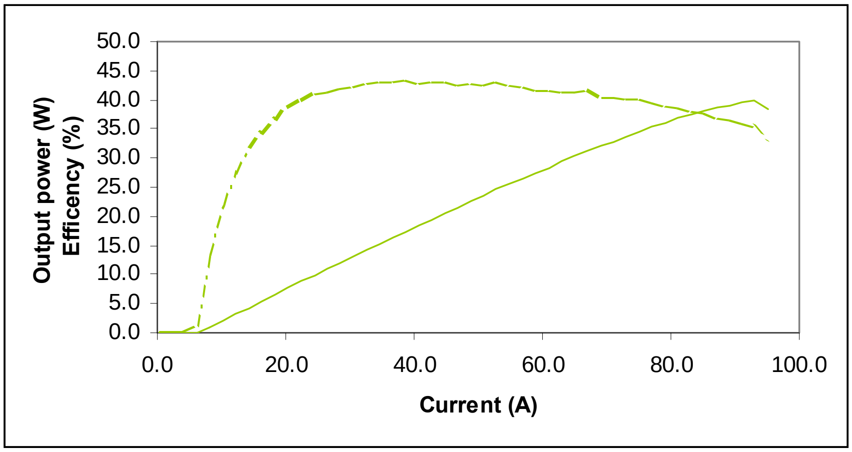

Figure 5. Using the same epitaxial design as used in Figure 4, the device is conductively using a CS-mount. The device cavity length is 100mm and the emitter width is 100μm for a total of 19 emitters. In spite of not being water-cooled, to the best of our knowledge, this is the best room temperature (25C) electrical-to-optical conversion efficiency, of 43%, for any high power laser bar operating in the 14xx-15xx regime.

3. CONDUCTIVELY-COOLED HIGH-BRIGHTNESS PUMP MODULE

For pumping of the solid state, efficient lasing is achieved by efficient absorption of the pump light in the solid state crystal and good overlap of the cavity optical mode with the pumped regions of the crystal. The laser cavity eigenmode is TEM_{00}; circularly symmetric with a Gaussian lateral profile. Ideally, the laser designer would like the pump optical mode profile to be close to that of the cavity eigenmode. This is best achieved through end-pumped configurations. Figure 6 illustrates the importance of pump brightness in end-pumping solid state laser rods. High brightness is also critical in free-space applications, such as direct diode IRCM, where low divergence beams are required to effectively transmit power over large distances.

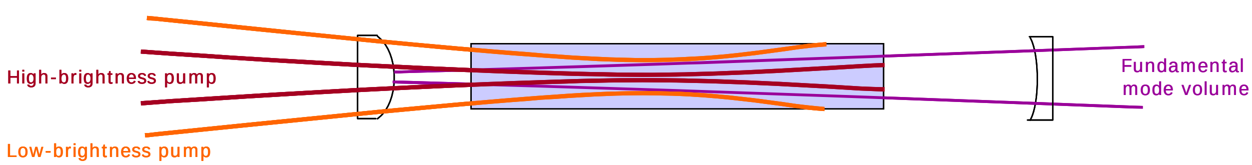

Figure 6: High brightness pumps have distinct advantages in the end pumping of solid state laser rods. Thermal lensing sets strict limits on pump power and linear absorption. Lower-doped, longer rods allow for higher pump powers. Longer rods require pumps with large Rayleigh range to overlap with TEM_{00} mode volume.

nLIGHT has been actively working to improve brightness of diode laser modules. To this end, nLIGHT has developed a new package based on arrays of singles emitters which offers the following advantages:

1. *Higher brightness*: Single emitters can be reliably operated at higher powers than emitters in a bar array. Fewer emitters are required to achieve similar operating powers to bars, improving M^2.
2. *Conductively cooled*: The physical separation of the emitters as compared to a bar eliminate neighbor heating and the requirement for water cooling

3. *Enhanced reliability*: AuSn hard solder permits higher operating powers without the creep associated with low melting point In solder. Active regions run cooler at a given output power compared to on a bar.
4. *Low cost*: Screening/qualification of individual ‘chiplets’ increases yield and leads to lower cost and higher reliability.
5. *Flexibility*: Any wavelength diode laser nLIGHT currently produces (from 600 to 2100 nm) can be packaged in this way. Multiple wavelengths from a single box are possible. Emitters can be wavelength-locked using volume Bragg gratings for spectral stabilization. The unit can be fiber-coupled or collimated for easier coupling to the solid state.

Brightness scaling in this format can be achieved through three independent approaches – increasing the number single emitters in the array, increasing the coupled power per single emitter in the array, and moving toward smaller diameter fiber / improved collimated beam quality. Continued innovation in the areas of diodes, optics, and packaging will enable ever-brighter products. Figure 7 illustrates a photograph of nLIGHT’s fiber coupled package in various configurations and the three independent paths toward brightness scaling. Figure 8 provides the power, voltage and efficiency curves for a CW 25W, 38% peak conversion efficiency, 400-mm core fiber Pearl unit [3].

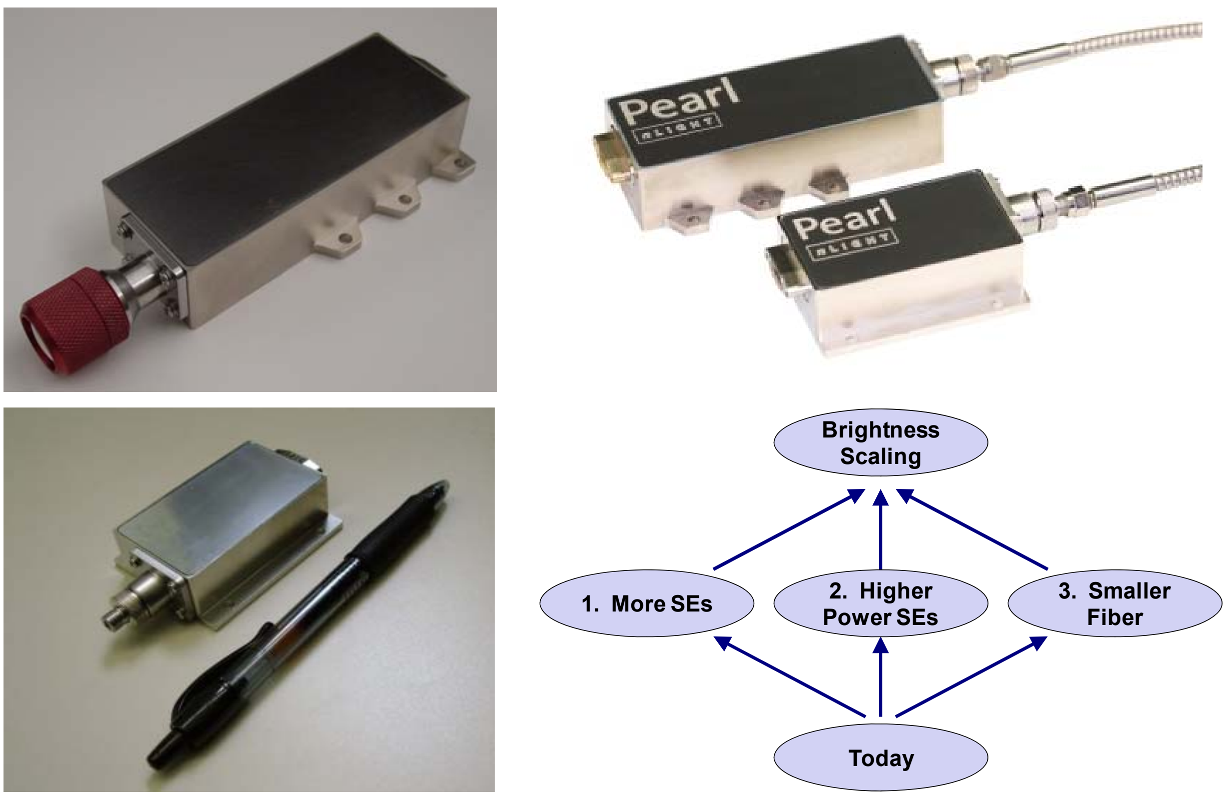

Figure 7: (Top left) Photograph of a conductively-cooled nLIGHT Pearl™ package with optional external lens for collimated output. This unit achieves a divergence of < 6 mrad (fast and slow axes) with beam diameter of < 9x12 mm (Top right) Two fiber-coupled nLIGHT Pearl™ modules. (Bottom left) Photograph of a Pearl™ module next to a common ink pen to emphasize its relative size. The unit weights ~500 grams. (Bottom right) Module brightness can be scaled in three independent ways. Coupling to smaller fiber is achieved through improvements in optical alignment and diode emitter brightness.

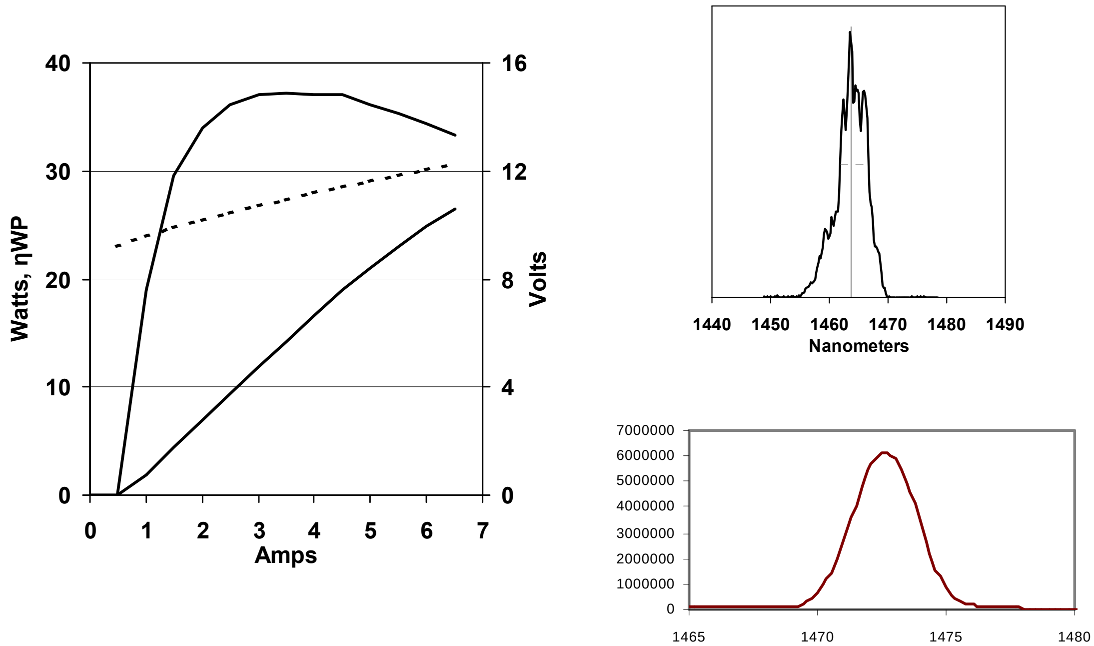

Figure 8: Left- Power, efficiency and voltage for a 25W, 1470-nm, Pearl unit coupled into 400-mm core fiber. Peak electrical-to-optical efficiency is 38% and~ 35% at the operating point. Top right- The unstablized full width at half maximum line width is ~5-nm. This spectrum is narrower than a bar of equivalent power because of the ability to bin individual emitters. Bottom right- Wavelength stabilized 1473-nm of 3-nm FWHM. Line widths of <1-nm are readily achievable depending upon choice of coatings.

A key enabling factor in this packaging approach is the ability to deliver high performance with high reliability through the use of hard (AuSn) solder with expansion-matched heatsinks. This technology is critical to military and space-based applications which require mean-time-to-failures (MTTFs) in excess of those achievable using water- and conduction-cooled solutions based on In solder and high thermal conductivity heat sinks. Excellent performance has been achieved with this high reliability approach. Figure 9 illustrates preliminary lifetest qualification data of a 1907-nm design, very similar to the 1470-nm diodes presented in he remainder of the paper (tests are still ongoing at the time of publication). To date, >18,800 total device hours (corresponding to >30,100 equivalent accelerated hours) have been demonstrated with virtually no performance degradation.

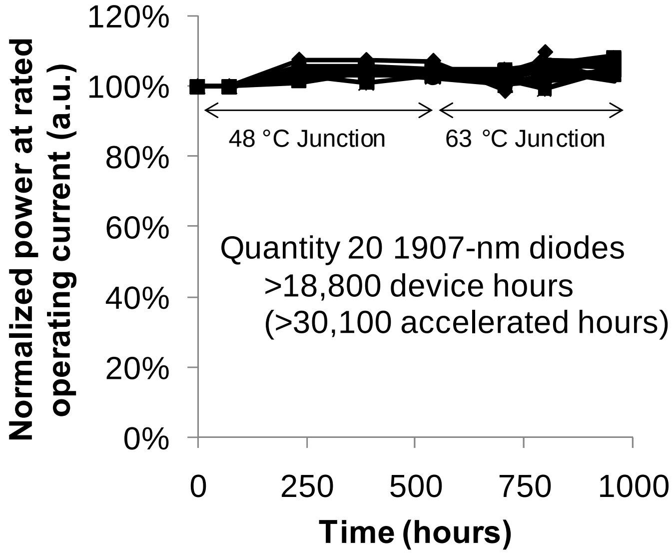

Figure 9: Preliminary reliability qualification data of 1907-nm Pearl emitters. To date, >18,800 total device hours have been logged with no observed performance degradation. Reliability testing is still ongoing at the time of publication.

4. CONCLUSION

Laser results at 1470-nm and life test results at 1907-nm have been presented. Record powers of 100W continuous wave, 50% electrical to optical efficiency and 25W into a 400- m core fiber with 38% peak electrical-to-optical efficiency, all at 1470-nm, have been demonstrated. Over 18, 800 device hours have been accumulated with no device degradation at the equally technically significant and similarly designed wavelength of 1907-nm.

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