Progress in Long-Wavelength High-Power Diode Laser Pump Sources

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A variety of applications are driving development of high power laser diodes operating between 1.4 and 2.1 µm. For example, Er-doped solid state and fiber lasers offer “eye-safe” alternatives to Nd- and Yb-doped lasers for use in military and industrial applications including range-finding, illumination, flash/scanning LADAR, and materials processing. Due to a reduction in quantum defect, direct diode pumping of Er lasers around 1.5 µm offers the potential for greatly increased system efficiency, reduced system complexity/cost, and further power scalability [1-2]. As another example, military, space, and medical applications benefiting from emission around 2.1 µm are driving development of Ho:YAG solid state lasers [3]. Efficient pumping of these systems can be achieved through direct diode pumping at 1.9 µm [4]. In this work, we describe recent progress in the development of high-power long-wavelength diode laser pump sources. For end-pumped rod and fiber applications requiring high brightness, nLIGHT has developed a flexible package format which is based on scalable arrays of single-emitter diode lasers. These modules can be efficiently fiber-coupled or be configured to provide a high-brightness collimated output. In this format, rated power in excess of 50 W and conversion efficiency in excess of 30% are reported for 1470-nm modules operating CW at 25 °C; rated power in excess of 18 W and conversion efficiency in excess of 10% are reported for 1900-nm modules operating CW at 25 °C.

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 [5]. The laser resonator TEM_{00} eigenmode is 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 9 illustrates the importance of pump brightness in end-pumping solid state laser rods. Additionally, power scaling in fiber lasers also requires pump modules with very high brightness.

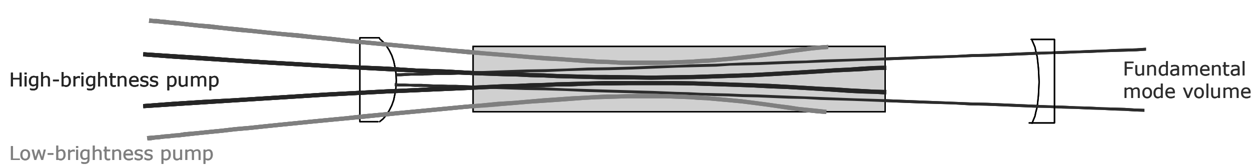

Figure 1. High brightness pumps have distinct advantages in the end pumping of solid state laser rods. Thermal lensing sets strict limits on pump power and linear absorption. Lower-doped, longer rods allow for higher pump powers. Longer rods require pumps with large Rayleigh range to overlap with TEM_{00} mode volume.

Given the brightness needs of these applications, nLIGHT has developed a package based on arrays of singles emitters (rather than cm-bar arrays) which offers the following advantages [6]:

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 beam quality (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 2 illustrates a photograph of nLIGHT's fiber coupled package and the three independent paths toward brightness scaling.

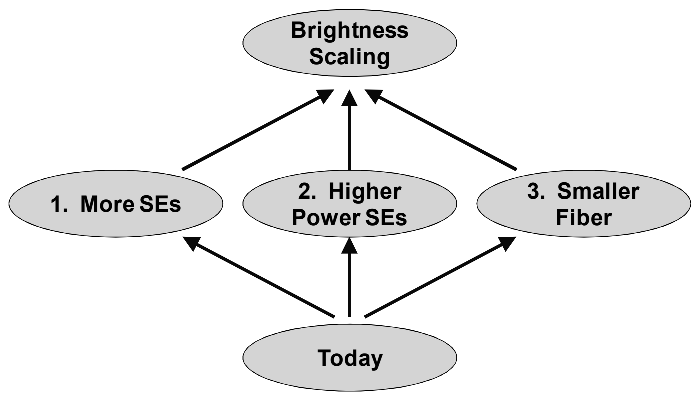

Figure 2. (Left) Photograph of a fiber-coupled module next to a common ink pen to emphasize its relative size. The unit weights ~500 grams. (Right) Module brightness can be scaled in three independent ways. Coupling to smaller fiber is achieved through improvements in optical alignment and diode emitter brightness.

Leveraging this approach, nLIGHT has recently demonstrated high power modules operating around 1470 nm and 1900 nm, thereby enabling low quantum defect end pumping of Er:YAG and Ho:YAG solid state lasers, as well as Er-doped fiber lasers. Figure 3 depicts results from the 1470-nm module, which demonstrates > 50 W (rated) CW and >80 W (rated) QCW (1 ms pulse width) with peak conversion efficiency in excess of 35% at 25 °C. Figure 4 depicts results from the 1900-nm module, which demonstrates 18 W (rated) CW and 25 W (rated) QCW (5 ms pulse width) at 25 °C. These units were measured with a collimated output, but could be efficiently (>90%) coupled to a 400- or 600-μm core fiber. Lower power units operating with similar efficient coupling to a 200-μm core fiber are also available. Higher powers and conversion efficiencies are available for units rated at lower temperature.

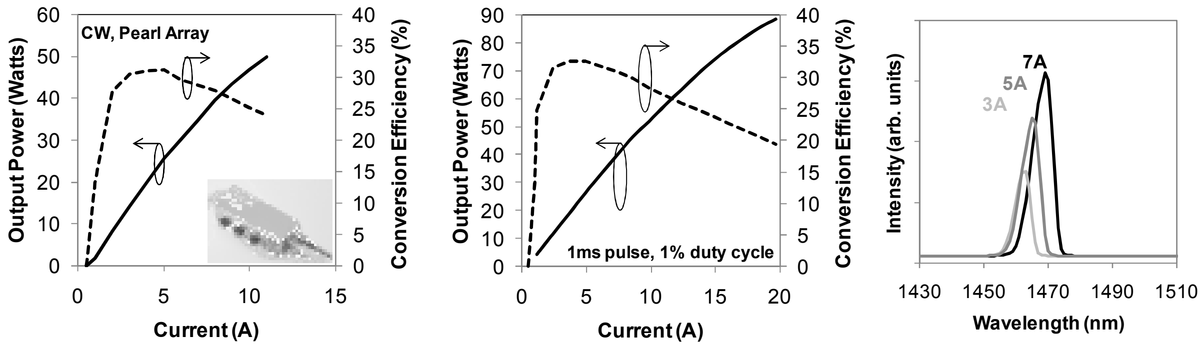

Figure 3. Module results at 1470 nm (measured afocal, >90% coupling efficiency to a 400-μm or 600-μm fiber also available; lower power units operating with similar coupling to a 200-μm core fiber also available). (Left) Under 25 °C CW operation, the 1470-nm unit delivers >50 W (rated) and >30% peak conversion efficiency. (Middle) Under quasi-CW (1% duty cycle) 25 °C operation, the 1470-nm unit delivers 90 W (peak). (Right) CW lasing spectra from one emitter in the array.

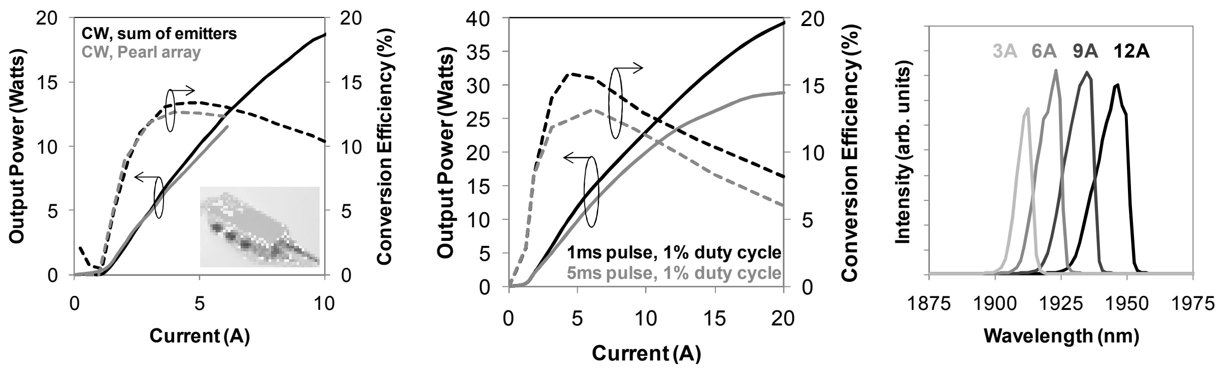

Figure 4. Module results around 1900 nm (measured afocal, >90% coupling efficiency to a 400-μm or 600-μm fiber also available; lower power units operating with similar coupling to a 200-μm core fiber also available). (Left) Under 25 °C CW operation, this unit delivers ~18 W (rated) and >13% peak conversion efficiency. (Middle) Under quasi-CW (1% duty cycle) 25 °C operation, this unit delivers 39 W (peak) for 1 ms pulse widths and 30 W (peak) for 5 ms pulse widths. (Right) CW lasing spectra from one emitter in the array.

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 heatsinks. Note that the poor temperature performance of long-wavelength diode lasers (relative to those operating at wavelengths below 1 μm), makes difficult the use of expansion-matched heatsinks (which typically have greatly reduced thermal conductivities). As a rule-of-thumb, at 1900-nm a factor two difference in thermal resistance translates to a factor of two difference in maximum output power. Nonetheless, excellent performance has been achieved with this high reliability approach. Figure 5 illustrates preliminary lifetest qualification data of the design (tests are still ongoing at the time of publication). To date, >23,900 total device hours (corresponding to >51,200 equivalent accelerated hours) have been demonstrated with virtually no performance degradation.

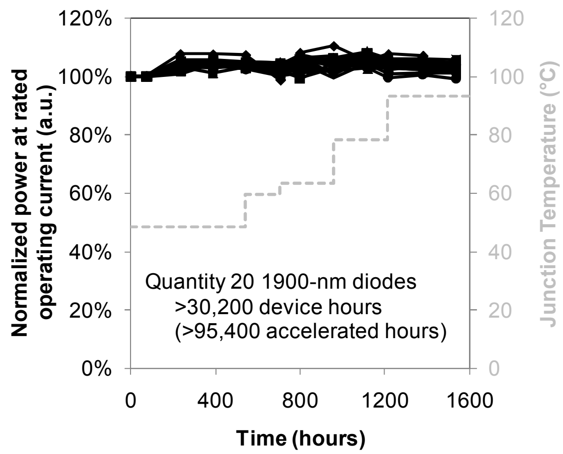

Figure 5. Preliminary reliability qualification data of 1907-nm constituent emitters. To date, >30,200 total device hours have been logged with no observed performance degradation.

Given the poor temperature performance of typical expansion-matched heatsinks, nLIGHT has begun research on novel expansion-matched materials which offer both compatibility with hard solders (for high reliability) and ultra low thermal resistance (for high performance). Figure 6 illustrates preliminary results (taken on 1900-nm lasers) illustrating the merit of the approach. Note all previous results in this work were obtained using the 'nominal' approach. As shown, at room temperature, the novel heatsink material improves the peak power by ~30%. At 10°C, the emitter delivers >2.2 W (peak) from a single 100 µm stripe.

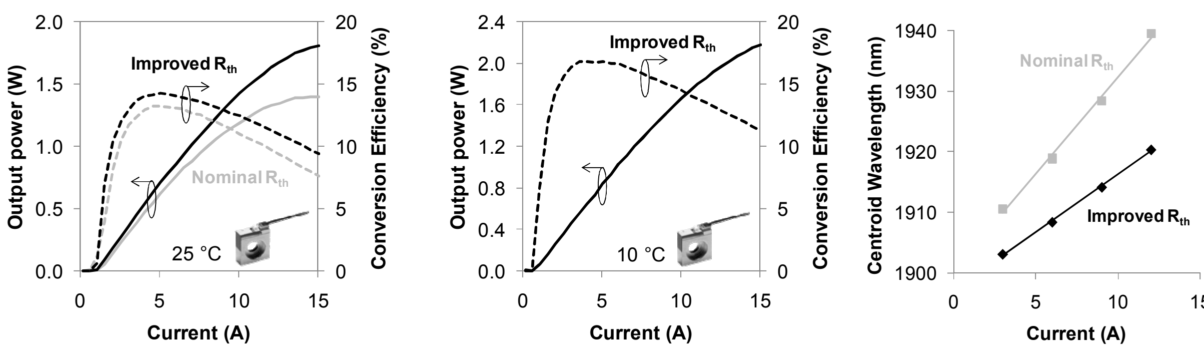

Figure 6. (Left) Novel expansion-matched materials with high thermal conductivity have recently enabled a ~30% improvement in power at 1900-nm. (Middle) At 10°C, the emitter delivers >2.2 W (peak) from a single 100-µm stripe. (Right) These results are achieved through a dramatic reduction in thermal resistance; this effect can be seen in the reduced drift of operating wavelength with drive current.

Further improvements to the temperature performance are expected to be enabled by laser epitaxy design refinement and heatsink materials research. For applications requiring high total powers, nLIGHT has also demonstrated results in microchannel-cooled cm-bar format. At 1470-nm, >100W per bar (45% conversion efficiency, tested CW at 10°C) has been demonstrated. At 1900-nm, >35W per bar (20% conversion efficiency, tested CW at 5 °C) has also been shown. These bars can be stacked into vertical arrays for scaling to very high total powers. For applications require spectral brightness and wavelength stabilization, nLIGHT has demonstrated wavelength locking by volume Bragg gratings. This approach has been shown to reduce the spectral emission width and wavelength temperature drift of the diode lasers by an order of magnitude, with <10% decrease in operating power [10]. Over the coming years, growing interest in efficient pumping of Er:YAG, Ho:YAG, and Er-doped fiber is expected to drive continued advancement in the performance of long-wavelength diode laser pump sources.

Acknowledgments

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