High-power diode lasers operating at 1800-2100-nm for LADAR and direct use in IRCM applications

ABSTRACT
A variety of applications are driving development of high power laser diodes operating between 1.8 and 2.1 µm. For example, military and space LADAR applications benefiting from low atmospheric absorption around 2.1 µm utilize Ho:YAG solid state lasers. Efficient direct diode pumping of these systems can be achieved with diode lasers operating around 1.9 µm. As another example, high power diodes operating at >2 µm are suitable for direct use in laser-based infrared countermeasure (IRCM) systems. In this work, we describe recent progress in the development of high-power long-wavelength diode laser sources. For applications requiring high brightness, nLIGHT has developed a conductively-cooled package format, possessing a footprint the size of a typical business card, which is based on scalable arrays of single-emitter diode lasers which can be efficiently coupled into a 400 µm core fiber. Under a NASA-funded SBIR contract, rated QCW powers in excess of 25 W are reported for modules operating at room temperature around 1900-nm. At 2050-nm, room-temperature QCW power in excess of 20 W in the same format is also demonstrated. In copper microchannel-cooled cm-bar format, we demonstrate greater than 37 W peak power and 23% peak conversion efficiency at 1900-nm and 25 W at 2050-nm.

Keywords: Diode laser, semiconductor laser, Ho:YAG, IRCM, mid-IR

1. BACKGROUND
Due to growing interest in applications requiring lasers which operate around 1.8 to 2.1 µm, diode laser technology in this wavelength band has been rapidly advancing [1-3]. For example, InGaAsP based 1900-nm lasers by nLIGHT have demonstrated >1.7 W CW from a 100-µm stripe single emitter [1]. Material built using the InGaAsSb material system has also advanced, with fiber-coupled modules delivering 15 W from a 600-µm core fiber [3]. Rapid commercialization of these technologies has ensued. Application segments driving this progress include medical, research, space, and defense. Due to a strong absorption peak in water, lasers operating close to 1900-nm are being utilized in medical fields such as dentistry, gallstone removal, eye surgery, and coronary angioplasty. The generation of 2- to 5-µm radiation in the research lab has historically been accomplished by the use of lasers which emit 2 µm radiation and then go through a complex series of wavelength conversions involving optical parametric oscillators (OPO’s).

Two applications which are of great importance to the defense industry include LADAR and infrared countermeasures (IRCM). Figure 1 illustrates the transmission spectrum of earth’s atmosphere [4]. The high transmission around 2 µm, makes this wavelength regime well suited for military and space LADAR and free space communication applications. This band has been traditionally accessed by Ho:YAG-based solid state lasers emitting at 2.1 µm [5]. Unfortunately, Ho:YAG does not have any suitable absorption feature in the traditional diode laser wavelength window of 785 to 980 nm, resulting in systems which are not directly pumped by traditional diode lasers. One common approach to the design of diode-pumped Ho-based lasers is to co-dope with Thulium, which can be directly pumped around 785 nm [6].
Unfortunately Tm-Ho:YAG lasers suffer from increased upconversion losses, resulting in shorter excited state lifetimes which limit laser performance [7-9]. Cascaded pumping schemes, such as intracavity pumping of Tm:YAG (or other Tm-doped crystal) and Ho:YAG crystals, or pumping Ho:YAG with Tm-doped fiber lasers, preserves the long excited state lifetime of singly-doped Ho:YAG (~8 ms), but the approach leads to greater laser system complexity, limiting the breadth of fieldable applications [7-8]. The maximum conversion efficiency of both approaches is also limited by the quantum defect which results from pumping at 795-nm. Direct diode pumping of singly-doped Ho:YAG is possible with diodes operating around 1.9 µm [9], thereby reducing the quantum defect and preserving the long excited-state lifetime of singly-doped Ho:YAG. This approach offers the promise of reduced system complexity, reduced cooling requirements, reduced cost, and improved reliability. See Figure 2.

Fig 1: Transmission spectrum of the earth’s atmosphere. The high transmission around 2 µm makes lasers which operate around this wavelength ideal candidates for military and space LADAR systems.

Fig. 2: (Left) Schematic of a intracavity diode-pumped Tm:YAG/Ho:YAG solid state laser. The Tm:YAG crystal is pumped at 785 nm and emits at 2013 nm, the Ho:YAG crystal and resulting in a laser system output at 2097 nm [7]. The quantum defect is >60%. (Right) Absorption spectrum of Ho:YAG around 1900 nm [8]. Ho:YAG can be directly pumped at 1907 nm [9], reducing the quantum defect to under 10%.

Another application of critical importance to the defense community is laser-based infrared countermeasures. Man-portable air-defense systems (MANPADS) are shoulder-launched, infrared “heat-seeking” missile systems which pose a critical threat to slow moving aircraft, such as helicopters and civilian airplanes [10]. These missile systems work by locking on to the mid-IR blackbody radiation heat signature of a hot object, such as the casing of a jet engine, guiding the missile to impact. Figure 3 illustrates the computed mid-IR blackbody emission spectrum of hot objects (at 500, 750, and 1000 °C). As shown, the peak emission occurs in the 2- to 3-µm regime, making mid-IR laser sources operating at these wavelengths attractive for countermeasure systems which seek to confuse the missile [11].
nLIGHT’s high-power 1.9 and 2.1 are based on strained InGaAs quantum wells grown by metalorganic chemical vapor deposition (MOCVD). Wafers follow nLIGHT’s standard broad area diode laser fabrication procedure. Laser bars are cleaved 1-cm wide with a 1.0-mm cavity length and 20% fill factor. The bars are coated and mounted junction down on copper microchannel-cooled heatsinks. Fig. 4 illustrates the output power and conversion efficiency of a single 1900-nm bar operating at 5 °C and 20 °C with 0.2-lpm water flow. As shown, the laser design achieves 35 W peak power and 23% power conversion efficiency at 5 °C. The performance is considerably less at 20 °C due to the strong wavelength and temperature dependence of Auger recombination rate [12].

Fig. 5 illustrates the output power and conversion efficiency of a single 2050-nm bar operating at 5 °C with 0.2-lpm water flow. The 2050-nm design achieves 25 W peak power and 19% peak conversion efficiency at 5 °C. The temperature performance of the 2050-nm design is noticeably worse than the 1900-nm. This is for two reasons. First, the wavelength dependence of Auger recombination rate (which strongly temperature sensitive) results in roughly twice the Auger recombination at 2050 nm than at 1900 nm [12]. Second, design modifications were required to push the Indium composition (and hence strain) in the quantum well high enough to obtain emission around 2050 nm [2, 12]. These design modifications are at odds with design for high temperature performance, resulting in the reduced temperature performance observed.
Fig. 4: (Left) A 1900-nm laser bar achieves 35 W peak power and 23% power conversion efficiency under CW operation at 5 °C with 0.2-lpm water flow. Increasing the temperature to 20 °C reduces the peak power to 25 W and the conversion efficiency to 19%. (Right) The bar has a spectral width 18.3 nm (FWHM) at 5 °C, 120 A.

Fig. 5: (Left) A 2050-nm laser bar achieves 25 W peak power and 19% power conversion efficiency under CW operation at 5 °C with 0.2-lpm water flow. Increasing the temperature to 20 °C reduces the peak power to 13 W and the conversion efficiency to 14%. (Right) The bar has a spectral width 15.1 nm (FWHM) at 5 °C, 110 A.

Single bars can be combined into vertically-stacked arrays to deliver high powers, as shown in Fig. 6. Each stack contains 10 bars on microchannel coolers. The 1907-nm stack was tested to 100 W (>200 W peak achievable) and showed 19% peak conversion efficiency at 15 °C with 0.2-lpm water flow. The 2050-nm design was tested to and rated at 70 W (> 140 W peak achievable) and operated at 14% peak conversion efficiency at 15 °C with 0.2-lpm water flow [2].
As was shown in Figure 2, the absorption feature around 1907-nm for Ho:YAG is quite narrow (around 3 nm FWHM). Efficient laser systems require that the diode pump source be equivalently narrow to ensure efficient absorption of the pump beam. The drift of operating wavelength with temperature of conventional diode lasers also sets strict requirements on thermal control of the diode pump source. Figure 7 illustrates the operating spectral width and wavelength temperature coefficient of nLIGHT’s single emitter diode laser products (operating at equivalent injection levels) across the spectrum. As shown, there is a clear dependence of both parameters on wavelength (A detailed description can be found in [13]). At 1907-nm, the spectral width of a broad area laser diode is greater than six times the spectral width of the associated absorption feature in Ho:YAG.

Fortunately, external locking of the longitudinal modes by means of a volume Bragg grating (VBG) can provide narrowing of the emission spectral width and reduction of the wavelength temperature coefficient [14]. VBGs are external optics with a periodically-varying index of refraction written into the glass. This structure achieves a spectrally-narrow reflection, which selectively feeds a portion of the light back into the diode laser cavity. This approach effectively decreases the threshold for the fed-back longitudinal modes such that they lase first and tend to dominate. As a result, power is efficiently diverted into just one (or a few) desired longitudinal modes. Figure 8 illustrates the emission spectrum of a 1907-nm laser bar which has been lensed and locked with a VBG. As shown, the FWHM has been reduced from ~20 nm to 2.7 nm, making it well-suited for pumping Ho:YAG. The residual broad emission which
lies outside the 2.7 nm width is a result of imperfect locking, and is attributed to residual broad-band reflection of the VBG (due to imperfect coating) or from the laser facet. The VBG-locked bar also operates with a 10% drop in power relative to the free-running case, though this could be reduced through further refinements in the optical coatings of the VBG and diode laser facet, and a better spectral alignment of the peak laser gain to the center of the VBG reflectivity spectrum.

Fig. 8: Spectrum of a free-running and VBG-locked 11-W laser diode bar operating at 1907-nm. The FWHM spectral width is reduced by a factor of six to 2.7 nm. This is accompanied by a 10% decrease in laser power. The imperfect locking is due to residual reflections from the lens or laser facet [2].

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 [15]. The laser resonator TEM$_{00}$ eigenmode is circularly symmetric; 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. High brightness is also critical in free-space applications, such as direct diode IRCM, where low divergence is required to effectively transmit power over large distances.

Fig. 9: 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 [16-17] 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 10 illustrates a photograph of nLIGHT’s fiber coupled package in various configurations and the three independent paths toward brightness scaling.

Fig. 10: (Top left) Photograph of a conductively-cooled nLIGHT Pearl™ package with optional external lens for collimated output. This unit achieves a divergence of $< 6 \text{ mrad}$ (fast and slow axes) with beam diameter of $< 9 \times 12 \text{ mm}$ (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 $\sim 500 \text{ grams}$. (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.
Fig. 11: Pearl™ results at 1900 nm (left column) and 2050 nm (right column). These units are measured afocal, though units with >90% coupling efficiency to a 400-µm or 600-µm fiber are also available. (Top) Under 25 °C CW operation, the 1900-nm unit delivers ~18 W (rated) and the 2050-nm unit delivers ~15 W (rated). Pearl™ array data indicate <4% loss due to the optics and were measurement-limited to 6 A. (Middle) Under quasi-CW (1% duty cycle), 25 °C operation, the 1900-nm unit delivers 39 W (peak) for 1 ms pulse widths and 30 W (peak) for 5 ms pulse widths. The 2000-nm unit delivers 25 W (peak) for 1 ms pulse widths. (Bottom) CW lasing spectra from one Pearl™ emitter from each unit taken at four different injection levels.
Figure 11 depicts nLIGHT Pearl™ results at 1900 and 2050 nm. The 1900-nm module demonstrates 18 W (rated) CW and 25 W (rated) QCW (5 ms pulse width) at 25 °C. The 2050-nm module demonstrates 15 W (rated) CW and 20 W (rated) QCW (1 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, depending on the application and customer needs. Higher powers and conversion efficiencies are available for units rated at lower temperature.

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 12 illustrates preliminary lifetest qualification data of the design (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.

4. CONCLUSION

Applications such as direct pumping of Ho:YAG for military and space LADAR and direct diode laser IR CM, have continued to drive development of diode lasers operating between 1800 and 2100 nm. nLIGHT’s Cascades™ microchannel-cooled cm-bar product line offers >15 W per bar (rated) in the 18XX to 19XX-nm band and >10 W per bar (rated) in the 20XX-nm band. These bars can be packaged into vertically-stacked arrays and/or VBG-locked for improved spectral performance. Due to the brightness requirements of end-pumped Ho:YAG and direct diode laser IR CM, nLIGHT has expanded its Pearl™ product line to include units operating between 1800 and 2100 nm. Operating at 25 °C, 18XX to 19XX-nm Pearl™ modules demonstrate 18 W CW and 25 W QCW (5 ms pulse width). Similar 20XX-nm Pearl™ modules demonstrate 15 W CW and 20 W QCW (1 ms pulse width). These units can be efficiently (>90%) coupled to a 400 or 600-μm fiber, or provide collimated output, depending on application needs. Higher powers and conversion efficiencies are available for units rated at lower temperatures. For applications requiring narrow, temperature-stabilized emission spectra, modules employing VBG-locking are also available. Preliminary reliability qualification demonstrates >18,800 total device hours with no observed performance degradation.
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REFERENCES


