# High-Power, High-Efficiency, High-Brightness Long-Wavelength Laser Diodes

Steve Patterson*, Paul Crump, Jun Wang, Weimin Dong, Mike Grimshaw, Shiguo Zhang, Sandrio Elim, Suhit Das, Mike Bougher, Jason Patterson, Guokui Kuang, Jake Bell, Jason Farmer, and Mark DeVito.

nLight Corp, 5408 NE 88th Ste, Bldg E, Vancouver, WA, USA 98665

**ABSTRACT**

Interest is rapidly growing in solid-state lasers emitting from 1500-nm to 2100-nm with applications in eye-safe range finding, LIDAR, infrared countermeasures, medicine, dentistry, and others. Traditionally, these solid-state lasers have been pumped by flash lamps or more recently, by semiconductor diode lasers. In the case of the latter, the diodes of choice have been those emitting below 1-µm. The sub-micron class of semiconductor diode lasers is highly mature and has enjoyed recent rapid advances in power and efficiency. Unfortunately, the quantum defect generated when converting to the desired wavelengths results in large amounts of excess heat generation leading to costly and heavy, expensive cooling systems and performance problems related to thermal lensing. System complexity adds further cost and weight when intermediaries, such as optical parametric oscillators, are required to reach the desired longer wavelengths. Recent advances in laser diodes emitting from 1400-nm to over 1900-nm now enable the near resonant pumping of such solid state media as Er:YAG, Ho:YAG and Cr:ZnSe. Record results in the peak output power and electrical-to-optical conversion efficiency of diode lasers emitting around 1470-nm, 1700-nm and 1900-nm are presented here.

**Keywords:** High-power laser, semiconductor laser, long-wavelength laser, InP lasers, solid-state laser pump lasers

## 1. Introduction

Solid-state lasers are the preferred source when single-mode output, high-peak power and a wide range of repetition rates and pulse widths are required from the laser. In particular, solid-state laser sources emitting from 1500-nm to 2100-nm have wide application in eye-safe range finding, LIDAR, infrared countermeasures, medicine, dentistry, and others. The historically most expensive and fragile element of the pumping scheme for these long wavelength solid-state lasers, the diode laser pump sources, have matured to where resonant diode pumping of the solid-state is now a realistic alternative to the more conventional Nd-based systems.

The diode laser pumping of solid-state lasers emitting in the 1500-nm to 2100-nm range places stringent demands upon the diode lasers. Ever higher peak pump powers are demanded of the > 14xx-nm diode pump lasers as a consequence of the three or quasi-four level nature of the solid-state lasers. The nature of three or quasi-four level lasers implies larger threshold power requirements than those found in true 4-level systems. Higher pump power is best achieved by increasing the power per laser bar (or, equivalently, higher bar brightness). Simply increasing the number of low power bars in the pump stacks adds considerable cost and complicates the efficient coupling of laser energy into the solid-state medium.

To achieve the desired improvements in long-wavelength 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 for a given active area temperature. High E/O efficiency lasers will also operate cooler at a given output power reducing the need for costly and heavy cooling capability. Hence, the design process emphasizes E/O efficiency as a method of achieving higher power.

In the following, Section 2 discusses the most important aspect physical process limiting long wavelength diode laser, Auger recombination. Section 3 begins with a discussion of recent results in Er:YAG eyesafe lasers and concludes with a discussion of 1470-nm diode lasers capable of producing 100W of peak power. Section 4 briefly explains the relevant aspects of the Ho:YAG laser and its limitations, concluding with the presentation of a 24W diode laser bar emitting around 1900-nm. The Cr:ZnSe laser has recently begun to grow in technical importance, a discussion of its desirable properties opening Section 5. Section 5 concludes with the presentation of a 22W diode laser emitting at 1700-nm. The work is summarized in Section 6.

## 2. Design of long-wavelength diode laser pump sources

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-µm. There are three major loss mechanisms that contribute to reduced diode laser efficiency and power:

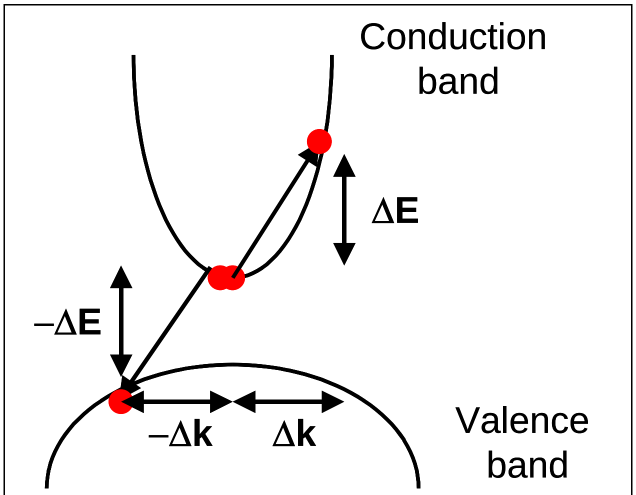

Figure 1 A schematic of the Auger process in semiconductors. An electron recombines with a hole acquiring momentum -ħk and releasing energy ΔE. Another electron acquires the energy ΔE and the momentum Δk. The excited electron will dissipate its excess energy as heat, often escaping the active region. 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.

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

Of these mechanisms, Auger recombination has the most deleterious effect on the performance of diode lasers emitting in excess of 1400-nm and will be discussed in greater detail here.

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- and AlInGaAs-material systems on InP substrates. 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).

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.

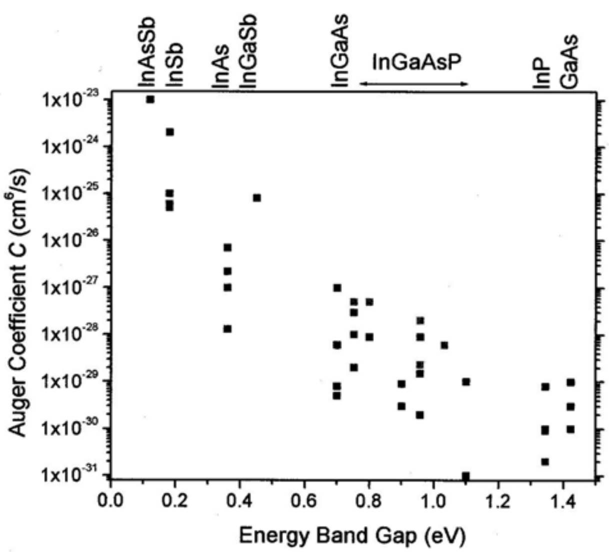


**Figure 3.12:** Auger coefficient *C* for direct-band-gap compound semiconductors at room temperature [47, 75, 77].

*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 [1].*

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.

The success and failure of diode laser design at wavelengths in excess of 1400-nm is measured in large part by the designer's ability to overcome or minimize the impact of the Auger process. This task becomes more difficult as the desired emission wavelength grows longer. In the following three sections, the properties of nLight diode lasers emitting in excess of 1400-nm are presented.

## 3. 14xx-nm Diode Lasers

Eyesafe laser systems wavelength range near 1.6 microns are typically based on frequency converted Nd:YAG lasers that are pumped with 808-nm quasi-CW laser diode stacks. These laser systems have many disadvantages. Key among these disadvantages include high cost, driven in part by the short upper state lifetime of Nd:YAG. The upper state lifetime of Er:YAG is between 5 and 10 milliseconds as compared to the Nd:YAG crystal whose upper state lifetime is roughly 200 microseconds. This lifetime disparity allows the Er:YAG crystal to be pumped 25 to 50 times longer than the Nd:YAG crystal. Equivalently, the same amount of energy can be stored in the crystal with far less pump power, thereby reducing cost by reducing the number of pump diode lasers required.

Nd:YAG lasers also suffer from relatively large size and low efficiency, driven by the need for an optical parametric oscillator (OPO) to perform the frequency conversion. In comparison, 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 as optical power loss conversion efficiency in OPOs is typically quite low. Other disadvantages of Nd:YAG include a large quantum defect (the maximum quantum efficiency is limited to only 808-nm/1540-nm = 52%) and diminished package ruggedness. Therefore, Er:YAG lasers pumped at 1470-nm offer an attractive alternative that improves electrical efficiency, lowers cost, and reduces package size. A conceptual schematic of these two approaches is shown in Figure 3.

Recently Setzler et al. [2], demonstrated the first 1470nm laser diode pumped Erbium laser. Using nLight laser diodes, the measured absorption coefficient of 0.5/cm implied 89% pump absorption in a 3cm long rod. This experiment serves as a very powerful proof-of-concept demonstration for a resonantly laser diode pumped Er:YAG laser emitting at the eye-safe wavelength of 1.645µm. One of the most exciting aspects of the Er:YAG system is the measured 5-7msec lifetime. This indicates that only a modest amount of average pump laser power is needed to achieve large pulse energy, short pulse width and high repetition rate lasers.

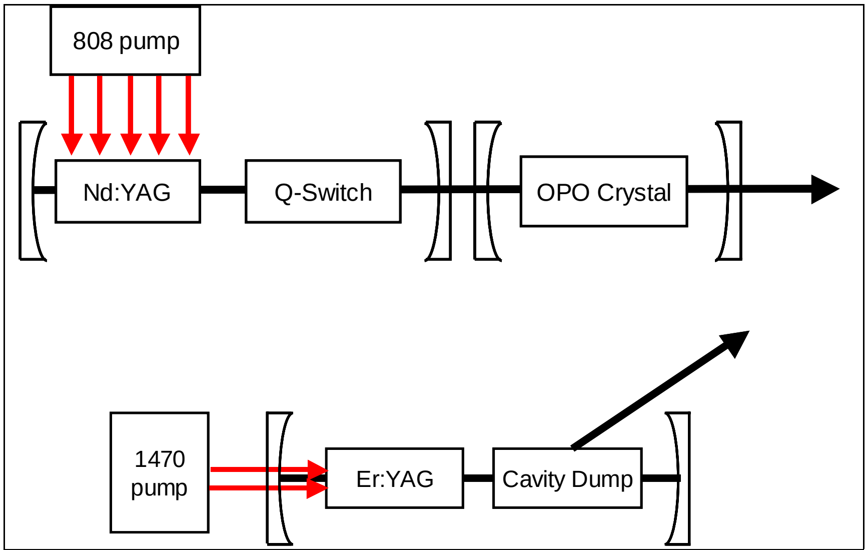


*Figure 3 – The figure shows a schematic comparison of a conventional 808-nm pumped Nd:YAG laser used to pump and OPO and the proposed approach of 1470-nm pumping of Er:YAG using a cavity dump. The proposed approach eliminates the need for an OPO improving efficiency and reducing size. Further, the long storage lifetime of Er:YAG dramatically reduces the required peak pump power thereby reducing the number of diode bars and hence cost.*

Key results demonstrated with this experiment included:

- Quasi-CW power of 30W at 10% duty cycle
- 47% slope efficiency Quasi-CW
- 26% optical conversion efficiency Quasi-CW
- $M^2$ = 1.4 X 2.2 (2.84 mm*mrad X 4.56 mm*mrad)
- 41mJ/58ns pulses operated Q-switched
- Storage lifetimes 5-7msec

Since the above demonstration, nLight has made significant advances in the power and efficiency of its 1470-nm laser bars [3]. 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 µ-channel cooler. 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). Both the 100W peak output power and the 42% room temperature conversion efficiency represent, best in class performance.

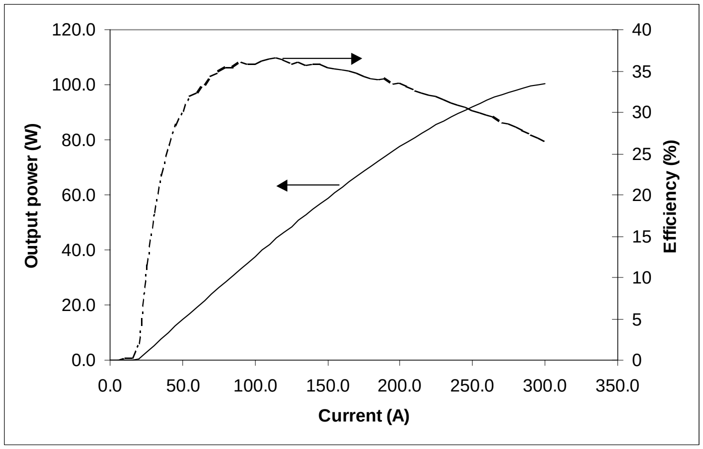


*Figure 4. Under ARO contract W911NF04C-0137, for the development of high-power, high-efficiency, 1470-nm diode laser bars, over 100W of CW output power was achieved with room temperature (20C) cooling water. This result represents best in class laser peak power.*

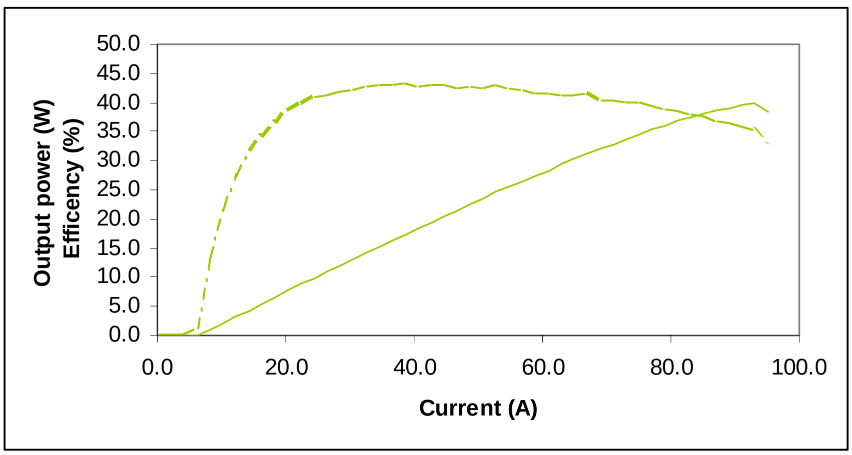


*Figure 5. Using the same epitaxial design as used in Figure 4, the device is now cooled using only a TE cooler. The device cavity length is 1-mm and the emitter width is 100-μm for a total of 19 emitters. This result represents best in class laser electrical-to-optical efficiency, either convection or conduction cooled bars.*

## 4. 19xx-nm Diode Lasers

Direct diode pumping of Ho:YAG, emitting at 2.1-μm, enjoys the same advantages as the previously described Er:YAG lasers: increased efficiency of the Ho:YAG laser and decreased thermal load and thus higher average power. To take advantage of this opportunity, high-brightness/high-power diode lasers, emitting near 19xx-nm, are needed for the direct pumping of the quasi 4-level $^5I_7$ to $^5I_8$ transition. Figure 6 provides a schematic of the reduction in system complexity achievable in direct diode pumping of Ho:YAG.

The Ho:YAG laser is often pumped by a Th:YAG laser, which is in turn pumped by a semiconductor diode laser emitting at 792-nm. Many of the drawbacks evident in the Nd:YAG system presented in section 3. are also present in the Th:YAG → Ho:YAG laser. An even larger quantum defect exists in the overall system transfer function in emitting at 2.1-µm while pumping at 792-nm. The introduction of a second of another solid-sate medium (Th:YAG) to pump the Ho:YAG introduces other similar issues as the previously described OPO- added complexity, weight, thermal management issues and usually most importantly, cost. Therefore, Ho:YAG lasers stand to benefit even more than Er:YAG from direct diode pumping.

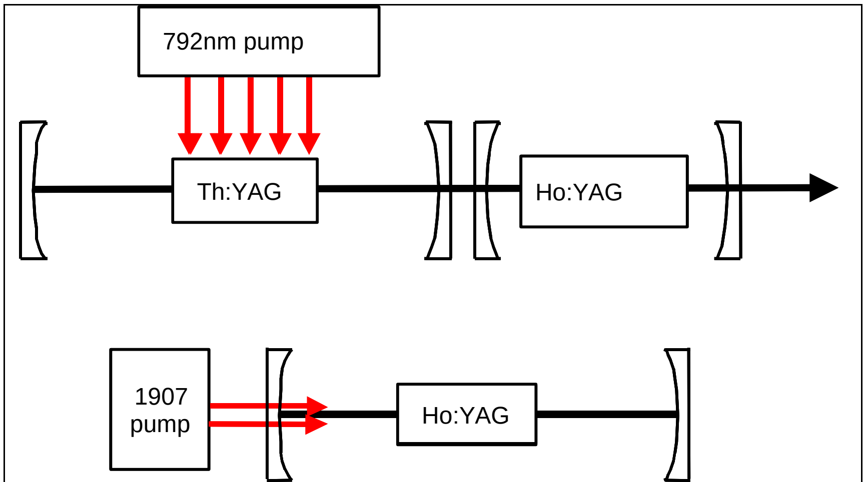


*Figure 6 – The figure shows a schematic comparison of a conventional 7xx-9xx-nm pumped Tm:YAG laser used to pump a singly-doped Ho:YAG laser and the proposed approach of 1907-nm direct diode laser pumping of Ho:YAG. The proposed approach improves efficiency and reliability as well as reducing size, weight and complexity. Further, the long storage lifetime of singly-doped Ho:YAG dramatically reduces the required peak pump power thereby reducing the number of diode bars and hence cost.*

Diode lasers emitting at 19xx-nm have additional challenges beyond the Auger recombination previously described. Foremost is the impact of the high levels of epitaxial strain needed to achieve these wavelengths. Low levels of crystal strain are normally designed into quantum well lasers to reduce the threshold current. At high levels of strain the crystal begins to accumulate crystal lattice defects degrading performance and lifetime. Even higher levels of strain can cause the active layers to relax entirely, destroying the intended properties of the crystal. Careful control of the growth conditions is required to minimize the impact of high strain levels [4].

Figure 7 shows a 1-cm diode laser bar emitting at 1900-nm having a peak optical output power of 23-W at 5-°C water and 0.5-lpm flow rate. The bar has 20% fill factor, 1.0-mm cavity length a on a copper µ-channel cooler. The diode laser material was grown using a commercial low-pressure MOCVD reactor after considerable growth optimization. As with most >14xx-nm diodes, thermal rollover limits the peak power of the bar. The absence of catastrophic optical mirror damage (COMD) is yet another advantage enjoyed by these longer wavelength semiconductor diode lasers as compared to their sub-micron counterparts.

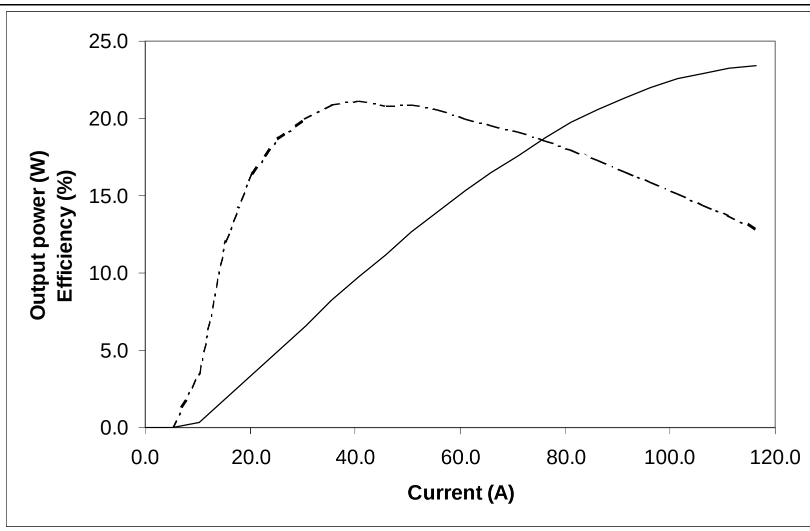


*Figure 7 - A 1-cm diode laser bar emitting at 1900-nm having a peak optical output power of 23-W at 5-°C water and 0.5-lpm flow rate. Peak power of 23-W and peak E/O efficiency of 22% are achieved.*

### 5. 1700-nm to 1850-nm Diode Lasers

Cr:ZnSe is not as well known as the Er:YAG and Ho:YAG lasers but enjoys some interesting and useful properties. Vibronic broadening in Cr:ZnSe leads to very broad absorption (~1500-2000nm) and emission (~2000-3000nm) (Figure 8). Cr:ZnSe also has a very high gain cross-section, considerably higher than Nd:YAG, and very high room temperature quantum efficiency. The main drawbacks are high dn/dT and short lifetime.

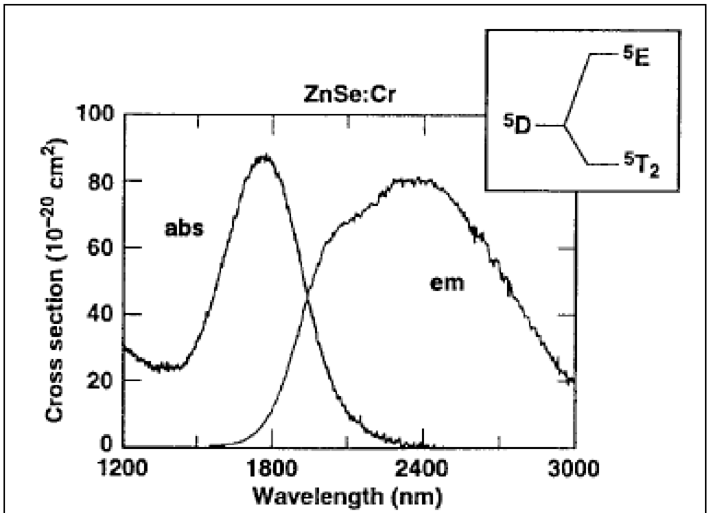


*Figure 8- The very broad absorption and emission spectra of Cr:ZnSe. [5]*

This highly attractive gain medium is pumped by laser diodes that share similar operating properties to those emitting at 1470-nm and around 1900-nm. Hence, the same diode laser design (Auger recombination) and growth issues (strain) apply. While not having been the target of as extensive a development effort as the other here described wavelengths, initial efforts targeted around 1700-nm have provided very encouraging results (Figure 9). It is expected that with continuing development effort that peak output powers and E/O efficiencies will approach those at 1470-nm.

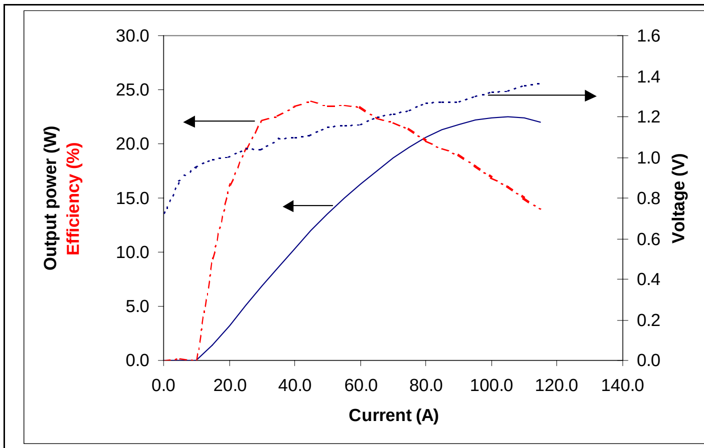


*Figure 9-Peak power of 23-W and peak E/O efficiency of 24% is demonstrated by a 1-cm wide, 1-mm long laser bar containing nineteen 100-um wide stripes. Emission is at 1700-nm. The bar was operated at 25C and 0.5 liters/min water flow.*

## 6. Summary

Laser results at 1470-nm, 1700-nm and 1900-nm have been presented. Record powers of 100W at 1470-nm, 23-W at 1700-nm and 24-W at 1900-nm have been demonstrated. These advances in the power and efficiency of high-power semiconductor diode lasers enable solid-state laser systems technologies emitting from 1500-nm to 2.1-μm and beyond, with reduced cost, complexity and weight and enhanced robustness.

## 7. Acknowledgements

S. Patterson would like to gratefully acknowledge Scott Setzler and Robert Delaney of BAE Systems and Greg Wagner of Lockheed Martin Coherent Technologies for helpful discussions.

Work to improve performance at 1470-nm is supported by Army Research Office under contract number: W911NF04C-0137.

## 8. References

1. J. Piprek, Semiconductor Optoelectronic Devices, Academic Press, 2003

2. Scott D. Setzler, Michael P. Francis, York E. Young, Jame R. Knoves, and Evan P. Chicklis: "Resonantly Pumped Eyesafe Erbium Lasers," IEEE J. Selected Topics in Quantum Electronics Vol. 11, No. 3, (May/June 2005).

3. Steve Patterson, Guokui Kuang, Paul Crump, Jun Wang, Mike Grimshaw, Weimin Dong, Sandrio Elim, Suhit Das, Damian Wise, Zack Huang, Mark DeVito and Jason Farmer: "100W High Power InP-based Diode Laser Bars" (2005) Proceedings of the 18th Solid State and Diode Laser Technology Review, Los Angeles, USA, Paper Diode 2-4.

4. Hong K. Choi (ed.): "Long Wavelength Infrared Semiconductor Sources", (2004) Wiley-Interscience, Hoboken, New Jersey, USA.

5. Ralph H. Page, Kathleen I. Schaffers, Laura D. DeLoach, Gary D. Wilke, Falgun D. Patel, John B. Tassano, Jr., Stephen A. Payne, William F. Krupke, Kuo-Tong Chen, and Arnold Burger: "Cr -Doped Zinc Chalcogenides as Efficient, Widely Tunable Mid-Infrared Lasers," IEEE J. Quantum Electronics Vol. 33, No. 4, (April, 1997).