76% efficient cryogenically-cooled eyesafe diode laser for resonant pumping of Er-doped gain media

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ABSTRACT

There is great interest in the development of high-power, high-efficiency InP-based broad area pump diode lasers operating in the 14xx-15xx nm band to be used for resonant-pumping of Er-doped solid state lasers. Cryogenic cooling of diode lasers can provide great benefit to performance, arising from the dramatic reduction in the threshold current and the increase in the diode's slope efficiency. These improvements are attributed to reduction in the non-radiative losses and leakage current associated with thermionic emission of carriers from the quantum well. This is, however, at the expense of a large increase in the diode voltage, limiting the power conversion efficiency at cryogenic temperatures. In this work, we report on the development of high-power, high-efficiency diode lasers and stacked arrays operating at 15xx-nm, which are specifically designed and optimized for operation at cryogenic temperatures. We show that the diode voltage defects under cryogenic operation can be greatly reduced through reducing the energy band offsets at the hetero-interface, and through material change to reduce the dopant ionization energy, effectively mitigating carrier freeze-out at low temperatures. Optical cavity designs and band engineering optimization are also explored for low intrinsic optical loss and low carrier leakage. A peak power conversion efficiency of >74% was demonstrated at a temperature of ~100K in a 15xx-nm single emitter. Record high peak conversion efficiency of 71% and peak power of > 500 W were also demonstrated in a stacked array, under QCW pulses of 1 ms and 10 Hz.

Keywords: Diode lasers, high efficiency, high power, eye-safe, DPSS, Er:YAG, cryogenic

1. INTRODUCTION

High-power solid state lasers operating beyond 1300 nm have been proposed as "eye-safer" sources in military applications such as directed energy weapons. Erbium-doped solid state lasers provide an attractive gain medium due to emission at eyesafe wavelengths [1], and the potential for ultra-low quantum defect pumping by diode lasers operating around 1532 nm [2]. As a result, there is currently great interest in the further development of high-power, high-efficiency diode lasers around 1532-nm to better enable efficient (direct) pumping of such laser systems. Operating solid-state lasers with cryogenically-cooled gain media has recently proven to be a viable path toward significant power scaling without loss of beam quality due to thermal distortions [3] in specific military applications where the cost implications are manageable. Er-doped media are shown to benefit most significantly from cryo-cooling [4]. Thus, in systems which are already equipped to provide cryogenic cooling to the solid state gain medium, the low marginal additional cost and effort of extending the cryogen to the semiconductor pump source makes it both feasible and practical, yielding a system which is overall highly efficient and power scalable. It is well-established that cryogenic cooling of diode lasers can provide great benefit to efficiency and power scaling. For example, Maiorov *et. al.* report >100% increase in the maximum output power of room-temperature optimized InP-based diode lasers cooled to 80K [5]. Here we report eye-safe diode laser design optimization for operating at cryogenic temperatures to further benefit power conversion efficiency and power scalability. A peak CW power conversion efficiency of >74% was demonstrated at a temperature of ~100K in a 15xx-nm single emitter diode laser. Record high peak conversion efficiency of 71% and peak power of >500 W (at ~100 K) were also demonstrated in a stacked array, under QCW pulses with a 1% duty cycle.

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There are three major loss mechanisms that contribute to imperfect operating efficiency in eyesafe diode lasers at room temperature: 1) carrier loss through Auger recombination, 2) optical losses through absorption and scattering, and 3) voltage drops across bulk layers and heterointerfaces. They are related to the threshold, slope and voltage of the diode lasers, respectively. At cryogenic temperatures, they are not necessarily the dominant losses anymore. To better understand the role each of the aforementioned loss mechanisms plays in reducing diode efficiency at cryogenic temperatures, it is helpful to represent them by their percentage contribution to the injected electrical power at various temperatures. An example is shown in Fig. 1, which illustrates the various losses and useful output in a 150-µm stripe, 1.5-mm cavity length, 15xx-nm diode laser that is optimized for operating at room temperature (the control design). As shown, the threshold current decreases dramatically from room temperature to liquid nitrogen temperature. The slope efficiency is also improved with decreasing temperature. However, the voltage loss (excess diode voltage drop beyond the photon voltage) is greatly increased at low temperatures. The key to improving performance lies in the understanding of the physical phenomena that are responsible for the observed temperature dependence, which is discussed next.

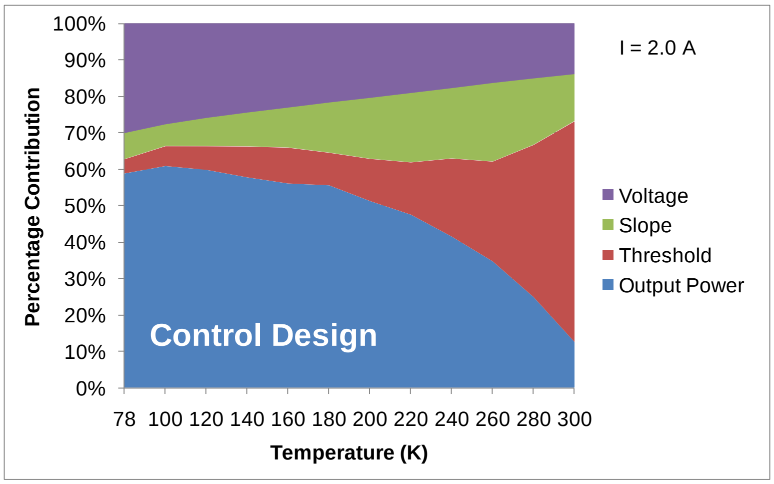

Fig. 1: Temperature dependence of main terms limiting efficiency for the control design with 1.5 mm cavity length, measured at a CW injection current of 2 A.

At cryogenic temperature, threshold current of eye-safe diode lasers is dramatically reduced. This is partly due to mitigation of carrier leakage at heterointerfaces owing to thermionic emission. Carriers confined to a quantum well can escape to the higher energy gap material if they possess sufficient thermal energy. Separately-confined heterostructure lasers designed for high efficiency must utilize carefully optimized band energy engineering to provide sufficient, but not excessive, carrier confinement. Generally, it is not desirable to make these energy differences too large, as the buildup of electric field at these interfaces can lead to high voltage defects. As temperature is decreased threefold from room temperature to liquid nitrogen temperature, the energy band which may have been previously optimized for room temperature operation is likely no longer the optimum design for high efficiency operation at cryogenic temperatures. On the other hand, suppression of non-radiative losses such as Auger recombination at cryogenic temperatures is also believed to contribute greatly to the reduction of threshold current. Auger recombination is a three-body phenomenon wherein the energy released through a carrier relaxation event is transferred to another carrier. While many such possible combinations exist, the dominant case in InP-based lasers is where an electron in the conduction band recombines with a hole in the valence band, and the energy released is given to another electron which is excited to a high energy state within the conduction band. This results in the loss of an electron hole pair, and possibly the loss of another electron (which have sufficient energy to overcome the confining heterobarriers). The Auger recombination coefficient is highly temperature sensitive. As the temperature is decreased from 300K to 77K, the Auger coefficient is reduced by ~40X [6], and this coefficient combines with the carrier density cubed (due to the three-body nature of the process), which itself is decreased by ~35X, to produce a three-order of magnitude reduction in the overall Auger recombination rate. This effectively renders Auger recombination insignificant at cryogenic temperatures.

Another key loss component to the overall efficiency of diode lasers is the intrinsic optical loss of the laser design. It encompasses all optical absorption and scattering processes which result in the loss of photons. The dominant absorption loss in InP-based diode lasers is believed to be intervalence band absorption (IVBA). Although the absorption coefficient does not depend strongly on temperature [7], the IVBA absorption does decrease due to freeze-out of excess carriers at low temperatures. Other loss mechanisms, such as optical scattering loss occurring at manufacturing defects in the optical waveguide and laser facets, do not vary much with temperature. It is not straightforward to know how the combined intrinsic optical loss varies as a function of temperature.

The primary challenge in achieving a fully optimized laser design is to reduce the diode voltage defect under cryogenic operation. The physical origins of the inverse dependence of voltage defect on temperature are the increased voltage defects at heterojunction interface and freeze-out of excess carriers in the doped semiconductor at low temperatures. Carriers transport across heterointerfaces is facilitated via thermionic emission. At low temperatures, the carriers possess less thermal energy to overcome the heterobarriers, which leads to increased turn-on voltage. Shallow-level dopant impurities in semiconductors (donors in n-type and acceptors in p-type) work by contributing excess majority carriers to the lattice, but only when sufficient thermal energy is present to ionize the electrons/holes from these elements. Because they reside very close to the appropriate band edge relative to the average thermal energy in the lattice at room temperature, nearly all impurities are ionized. The ionization process follows Fermi-Dirac statistics, and as a result, ionization probabilities (and therefore free carrier concentration) exhibit an exponential dependence on temperature, which is characterized by a thermal activation energy given by half the ionization energy of the dopant species in the crystal. Both effects lead to a greatly increased voltage loss at low temperatures, as shown in Fig. 1. This is the fundamental reason why diode lasers must be redesigned and specifically optimized for use at cryogenic temperatures. Simply put, the design rules change: one must intentionally take advantage of the super low threshold current and mitigate the high voltage defect to fully realize the benefits of cryogenic cooling.

2. EXPERIMENTS

Based on the above understanding around the key physics of operation and limitations of InP-based diode lasers at cryogenic temperatures, and leveraging nLight's high-power, high-efficiency 15xx-nm laser designs, multiple epitaxy designs have been grown that are specifically designed and optimized for use at cryogenic temperatures. The structures were grown on S-doped InP substrates following nLight's established MOCVD processes. All wafers were processed following nLight's standard InP wafer fabrication protocols. Single-emitter laser diodes of 150-μm stripe width and 1.5-mm cavity length were cleaved, coated, and bonded to industry-standard Cu c-mounts with In solder, except for in the cavity length analysis, where single emitters with cavity lengths of 1.0, 1.5 and 3.0 mm were cleaved. Bars of 1.5-mm cavity length and 30% fill factor are also processed and bonded either to industry-standard Cu CS-mounts using nLight's highly-reliable AuSn hard solder process, or multi-bar stacked array for power scalability.

nLight completed the design, installation, and qualification of a cryogenic temperature test station for testing single emitters, bars and arrays in CW and QCW mode from 350 K to 25 K. The optical cryostat system, acquired from ColdEdge Technologies, is capable of supplying high current of up to 300 A through high current feed-throughs and maintaining >200 W heat dissipation at 77 K (through a closed-loop cryo-cooler system). Testing fixtures were designs to accommodate c-mount single emitters, CS-mount bars, and stacked arrays. Testing occurred in an evacuated cryostat test chamber, with the cryostat window anti-reflection coated with minimum reflection near 1.5 μm. Light-current-voltage characteristics of the devices were measured at various cold finger temperatures. The output power was measured using a NIST traceable thermopile, and the spectrum measured using an optical spectrum analyzer.

3. DESIGN OPTIMIZATION FOR CRYOGENIC TEMPERATURES

3.1 Mitigation of voltage defect at cryogenic temperatures

Design of a diode laser structure which achieves optimal efficiency at cryogenic temperatures requires mitigation of the voltage defect. Strategies for reducing voltage may include increasing doping density, reducing energy band offsets at the heterobarriers, or changing materials to reduce the dopant ionization energy, thereby preserving relatively higher carrier densities as the temperature is reduced. Fig. 2 depicts the design approaches adopted in this work to mitigate the voltage loss. As described earlier, suppression of thermionic emission at low temperatures allows the reduction of the bandgap energy of the waveguide materials, which still provides sufficient carrier confinement, but leads to reduced voltage defects at the heterointerfaces, hence a lower turn-on voltage. A low voltage design (design #1) was developed, which features an InGaAsP waveguide material of lower bandgap energy. Fig. 3(a) plots the temperature dependence of various losses measured in a single emitter device of the design with 1.5 mm cavity length, tested at a CW injection current of 2 A. The design has improved voltage loss of 20% at 80 K, compared to 30% in the control design (Fig. 1). This results in 65% peak conversion efficiency over the 60% demonstrated in the control design at cryogenic temperatures [Fig. 3(c)].

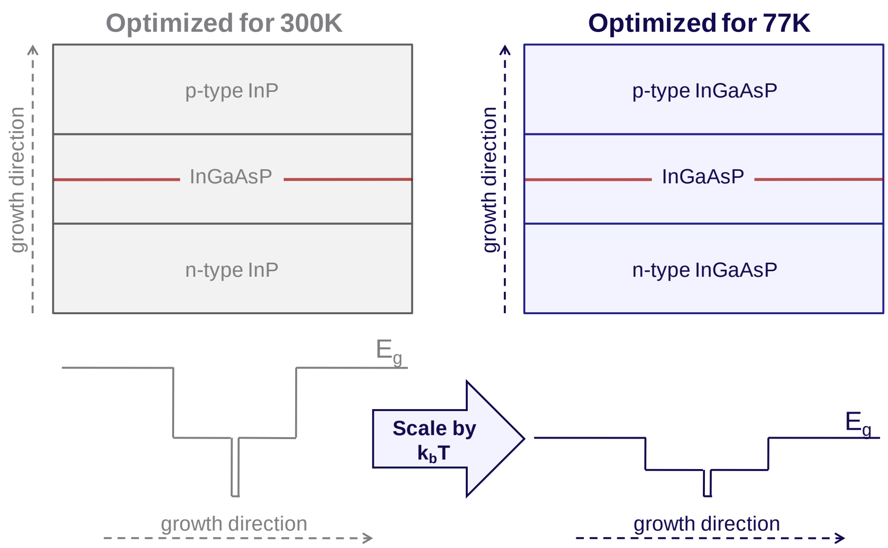

Fig. 2: Schematics of design approaches and band diagrams for mitigating voltage defect at low temperatures.

Dopant freeze-out (especially for holes) can cause a dramatic decrease in the bulk conductivity of the epitaxy structure. This freeze-out can be mitigated by an increase in carrier mobility or use materials with reduced activation energy. To investigate the effect of dopant freeze-out and mobility on the overall conductivity in the bulk layers, samples of InP and $In_{0.90}Ga_{0.10}As_{0.24}P_{0.76}$ were grown with Zn doping ($>1x10^{18}$ cm^{-3}) and assessed by cryogenic hall effect measurements. Fig. 4(a) illustrates the measured carrier concentration and mobility as a function of temperature for the two materials. The measured carrier concentration fits well to a logarithmic function, allowing a straightforward extraction of the dopant ionization energy [8]. The obtained values for ionization energy of Zn in bulk InP and $In_{0.90}Ga_{0.10}As_{0.24}P_{0.76}$ are 18.6 meV and 11.6 meV, respectively. The incorporation of Zn in InGaAsP offers close to two-fold reduction in the activation energy. On the other hand, the hole mobility of the InGaAsP is lower than that of the InP throughout the whole temperature range [Fig. 4(a)], although the difference can be compensated by increasing Zn doping density in InGaAsP. In Fig. 4(b), the relative resistivity of the two materials (normalized to the room temperature resistivity) is plotted as a function of temperature. InGaAsP is shown to offer >25% improvement in bulk resistance at 77 K. The findings motivated a design change of the laser epitaxy – the material system of the p-cladding was switched from the traditional InP to InGaAsP. Low voltage design #2, which also uses InGaAsP as the n-cladding material, is shown in Fig. 3(b) to further reduce the voltage loss (10% voltage loss at 80 K). The improvement in both turn-on voltage (due to lower bandgap InGaAsP cladding that reduces voltage defect at waveguide-cladding interface) and series resistance, as evident in Fig. 3(d), leads to a peak conversion efficiency of over 70% [Fig. 3(c)]. Note that this change would have been impractical for a laser designed for room-temperature operation; this is because the wide bandgap of InP is of critical importance to the suppression of thermionic emission loss of electrons to the p-cladding.

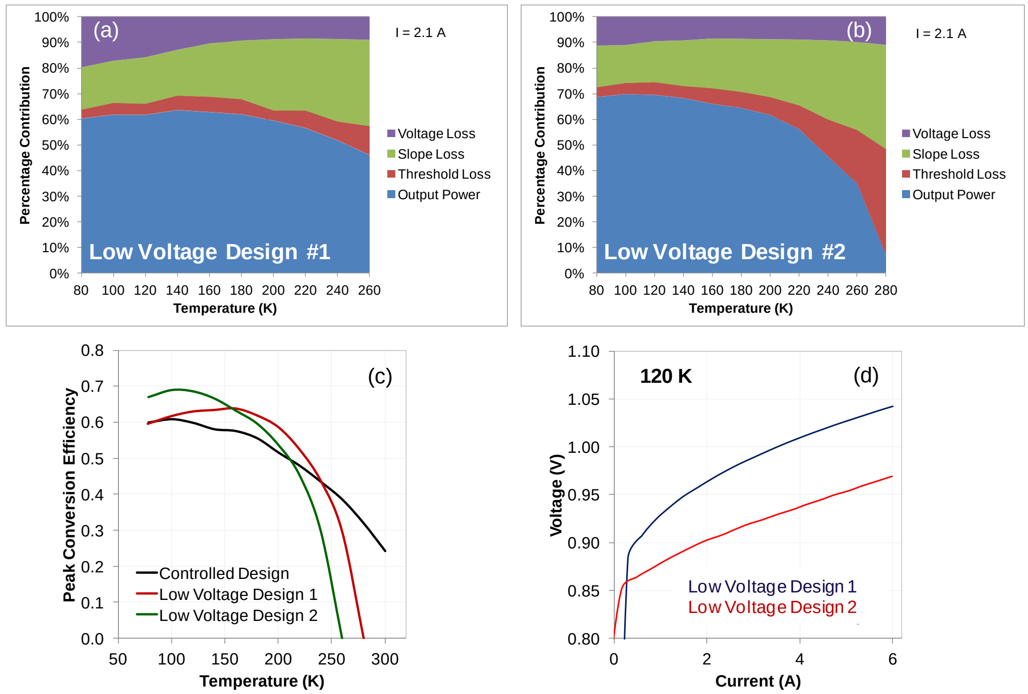

Fig. 3: Temperature dependence of main terms limiting efficiency for (a) low voltage design #1 and (b) low voltage design #2 with 1.5 mm cavity length, measured at a CW injection current of 2 A. (c) Peak conversion efficiency as a function of temperature for both designs.

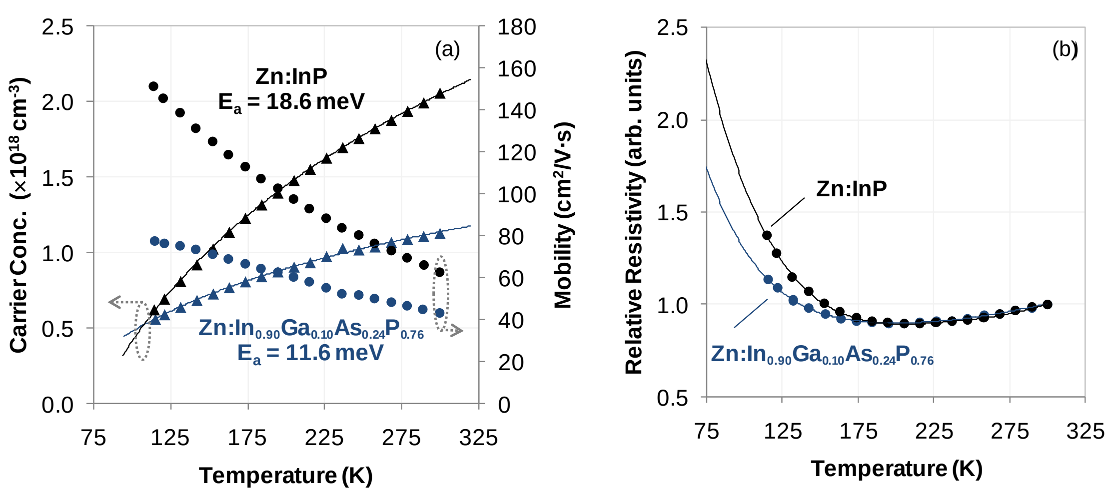

Fig. 4: (a) Measured carrier concentration and mobility versus temperature for Zn p-type dopant in InP and $In_{0.90}Ga_{0.10}As_{0.24}P_{0.76}$. (b) Relative bulk resistivity versus temperature for the two materials.

3.2 Cavity length analysis

While the voltage losses of the cryo-cooled eye-safe diode laser were greatly reduced in the low voltage designs #1 and #2, it is evident in Fig. 3 that the slope losses in both designs are higher than that in the control design, and become the main loss mechanism that limits the conversion efficiency at cryogenic temperatures. The slope efficiency, or the external differential efficiency (η_D) of the laser diode is related the internal quantum efficiency η_i and losses. It can be expressed in terms of $\eta_D = \eta_i\alpha_m/(\alpha_m+\alpha_i)$, with $\alpha_m = \ln(1/R_1R_2)/2L$ the mirror loss and α_i the internal optical loss. η_i and α_i can be determined from the linear fit to inverse η_D versus cavity length L (so called cavity length analysis) [9]. To reveal the origin of the low slope efficiency, single emitters with cavity lengths of 1.0, 1.5 and 3.0 mm of the control and low voltage designs were tested at various temperatures. The extracted η_i and α_i at various temperatures are plotted in Fig. 5 for both the control and low voltage designs. η_i of the control design tends toward 100% at low temperatures, indicating a total suppression of leakage current. The large value of optical loss (>3 cm^{-1}) at room temperature is believed to be due to strong IVBA at the quantum wells and the p-cladding. The optical loss decreases with decreasing temperature, but remains close to 1 cm^{-1} at cryogenic temperatures. The non-vanishing optical loss is related to the free carrier absorption in the quantum wells and scattering loss, and it is likely that the IVBA in the p-cladding still contributes even as holes freeze-out in the cladding at low temperatures. On the other hand, the optical loss in the low voltage design has similar value to that in the control design at low temperatures [Fig. 5(b)]. However, the internal quantum efficiency is below 80% even at 77K, which becomes the main limiting factor to conversion efficiency. In the low voltage design, a lower bandgap energy InGaAsP waveguide was used to reduce voltage defects at heterointerfaces. It is likely that the carrier overflow is significant even at low temperatures, due to the insufficient barrier height provided by the waveguide. To further improve the performance of cryogenically cooled diode laser, the imperfect internal quantum efficiency needs to be improved (and possibly optical loss at p-cladding as well).

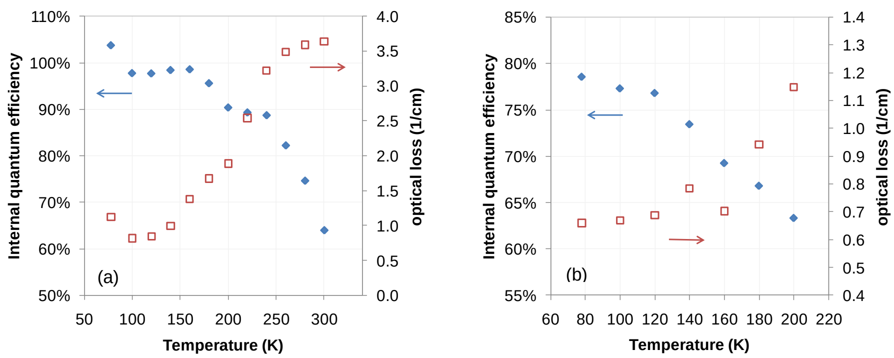

Fig. 5: Internal quantum efficiency (η_i) and optical loss (α_i) as a function of temperature for (a) the control design and (b) low voltage design #1, retrieved from the cavity length analysis.

3.3 Waveguide design optimization

Design optimization to further increasing the peak conversion efficiency at cryogenic temperatures was carried out based on the low voltage design #2. This included waveguide optimization that minimizing mode penetration into the p-cladding for low intrinsic optical loss, and bandgap engineering to mitigate carrier overflow (imperfect internal quantum efficiency) without significantly increasing the voltage defect at low temperatures. Fig. 6 shows the measured light-current-voltage and peak efficiency at various temperatures for the best design out of the effort. As shown, the design achieves >74% CW peak conversion efficiency at temperatures between 100 and 140 K. Temperature dependence of the loss mechanisms [Fig. 6(c)] reveals the origin of conversion efficiency improvement, which results mainly from the slope efficiency improvement at low temperatures. This is accompanied by slight increased voltage loss. The threshold current remains as low as in the other experimental designs. The peak efficiency drops quickly as the temperature is raised beyond 200 K, until the laser stops lasing at temperatures above 260 K. This is due to the low bandgap energy of barriers that is insufficient to suppress the thermionic emission, leading to a radically increased threshold current at higher temperatures. The fact that the cryogenically optimized laser design does not lase at room temperature implies significant difference in the design methodology at different temperature regimes. The conversion efficiency also starts to fall under temperatures below 120 K, due to increased voltage loss that eventually dominates at very low temperatures.

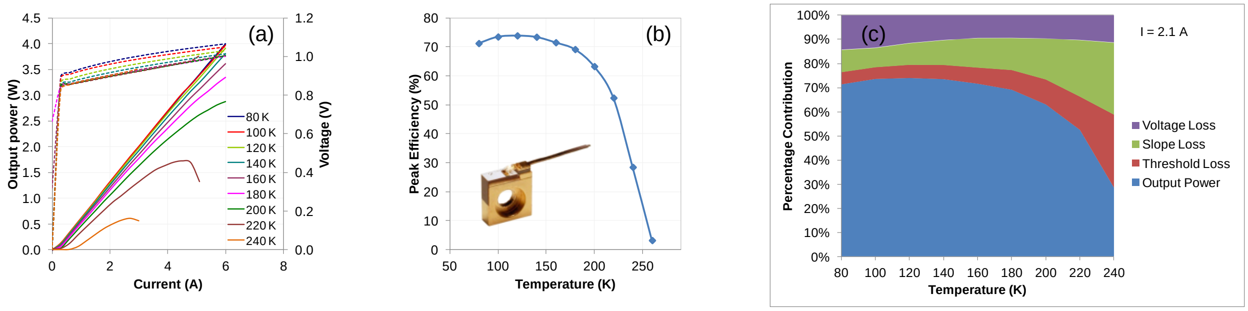

Fig. 6: (a) Light-current-voltage characteristics of the waveguide optimization design at various temperatures. (b) The peak conversion efficiency of the design as a function of temperature, demonstrating >74% CW efficiency between 100 and 140 K. (c) Temperature dependence of main loss mechanisms in the design limiting conversion efficiency.

3.4 High power and high efficiency QCW bars and arrays

The waveguide optimization design was also fabricated into 30% fill factor 1-cm wide bars, which were bonded to industry-standard Cu CS-mounts. As shown in Fig. 7(a), the single-bar diode laser demonstrated >90W optical powers and record high 76% peak conversion efficiency under QCW pulse duration of 1 ms and repetition rate of 10 Hz (1% duty cycle), both record high among eye-safe diode laser bars to the best of our knowledge. The CS-mounted bars scale up power while maintain high conversion efficiency in the single-emitter devices. The inset of Fig. 7 displays the lasing spectra that have center wavelength ranging from 1480 to 1540 nm.

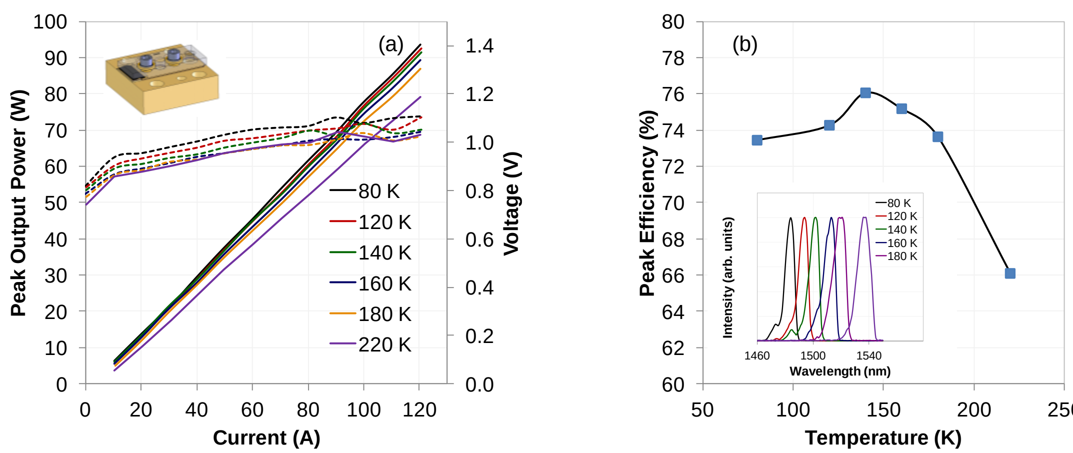

Fig. 7: (a) Light-current-voltage characteristics of the CS-mounted diode laser bar tested under pulse duration of 1 ms and repetition rate of 10 Hz. (b) The peak conversion efficiency demonstrating >76% QCW efficiency. (Inset) Lasing spectra under various temperatures.

A prototype high power QCW stacked array was fabricated to demonstrate power scaling under cryogenic temperatures. 6 bars with 1-cm width and 30% fill factor were vertically stacked with a bar-to-bar pitch of 400 μm. The package is flexible (4 to 10 bars can be arrayed in a single package) and utilizes CuW insert heatsinks between bars to spread heat and provide coefficient of thermal expansion matching to the laser bars. The performance of the array under various temperatures was shown in Fig. 8. Record high peak conversion efficiency of 71% (at 100 K) and peak power of > 500 W at 120 A driver current were demonstrated, under QCW pulse of 1 ms duration and 10 Hz repetition frequency. The bar count in the array was determined so that it delivers >500 W optical power. The power can be further scaled up with more bars in the array and higher driver current. A less efficient design (than the waveguide optimization design) was used in the fabricated array due to material availability. The same design was tested to yield 72% peak efficiency in the CS-mount platform (data not shown), confirming efficiency equivalency in the 6-bar stacked arrays and CS-mounted bars. It is therefore expected that array made out of the waveguide optimization design should be able to yield a peak conversion efficiency of about 75%. The inset of Fig. 8 plots the lasing spectra at cryogenic temperatures that range from 1480 to 1510 nm.

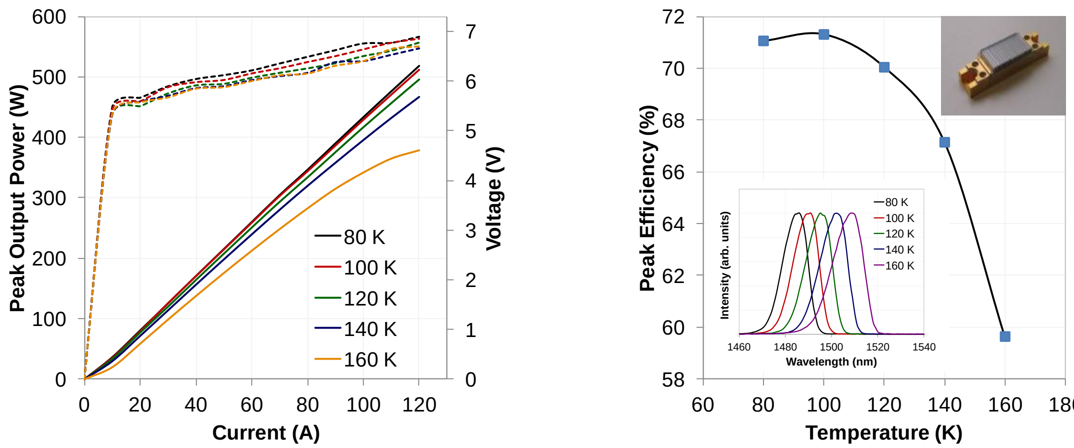

Fig. 8: (a) Light-current-voltage characteristics of the 6-bar stacked array tested under pulse duration of 1 ms and repetition rate of 10 Hz. (b) The peak conversion efficiency demonstrating >71% QCW efficiency. (Inset) Lasing spectra under various temperatures.

4. CONCLUSION

In summary, high power diode lasers operating at 15xx-nm were designed and optimized for efficient operation at cryogenic temperatures. We show that diode voltage defects under cryogenic operation can be reduced through reducing the energy band offsets and mitigation of carrier freeze-out at low temperatures. Optical waveguide designs and band engineering optimization were also explored for low carrier overflow and intrinsic optical loss, without significantly increasing the voltage defect at low temperatures. A peak CW power conversion efficiency of >74% was demonstrated in a cryogenically optimized single-emitter design at a temperature of ~100K. Record high peak conversion efficiency of 71% and peak power of >500 W were also demonstrated in a stacked array, under QCW pulses with a 1% duty cycle. We also demonstrated 76% efficiency on bars mounted on CS heatsink operating under QCW operation of 1 ms and 10 Hz. With the understanding of the various loss mechanisms limiting efficiency at cryogenic temperatures in the developed designs, it is possible that further design optimization can be achieved through, for example, facet coating optimization or applying carrier blocking schemes to improve internal quantum efficiency with minimum voltage penalty.

5. ACKNOWLEDGEMENT

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