Conversion Efficiency Optimization of Cryogenically Cooled 15xx nm InP Diode Lasers

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Abstract: Performance of two InP diode laser designs are studied at various temperatures and through cutback experiments. Conversion efficiency is shown to be limited by excess voltage and thermionic emission of carriers at cryogenic temperatures.

OCIS Codes: (140.5960) Semiconductor lasers; (250.5590) Quantum-well, -wire, and -dot devices

1. Introduction

Resonantly diode pumped Er-doped lasers are currently viewed as the most promising path to a highly scalable, eye-safe, bulk solid-state laser source [1,2]. As a result, there is currently great interest in further development of high-power, high-efficiency InP-based broad area diode pump lasers operating in the 14xx-15xx nm wavelength range for resonant pumping of Er-doped lasers [3]. Cryogenic cooling of Er-doped solid-state laser gain media has the advantage of efficient power scaling without loss of beam quality due to thermal lensing. It is also well established that cryogenic cooling of diode lasers can provide great benefit to efficiency and power scaling. Thus, developing Er-doped solid-state lasers with unified cryogenic cooling for both gain medium and diode pumps provides a path towards a highly efficient eye-safe laser source with very high brightness.

When the temperature of the diode laser is reduced, the threshold current density is reduced, and the slope efficiency increases, as a result of reduced Auger recombination, thermionic emission of carriers and optical losses. These benefits are tempered by the freeze-out of excited-state dopant carriers and increased built-in voltage, resulting in a corresponding rise in the diode voltage and effectively limiting the maximum achievable conversion efficiency. Recently, we have reported a laser design with an InGaAsP p-cladding layer that achieves a large decrease in voltage defect relative to a more traditional InP design, and a peak conversion efficiency of ~70% at 77K [4]. Here we present temperature dependent efficiency study to diagnose the physical mechanisms limiting the performance of the two diode laser designs. A cutback experiment was also performed to better assess the internal quantum efficiency and optical loss at cryogenic temperatures.

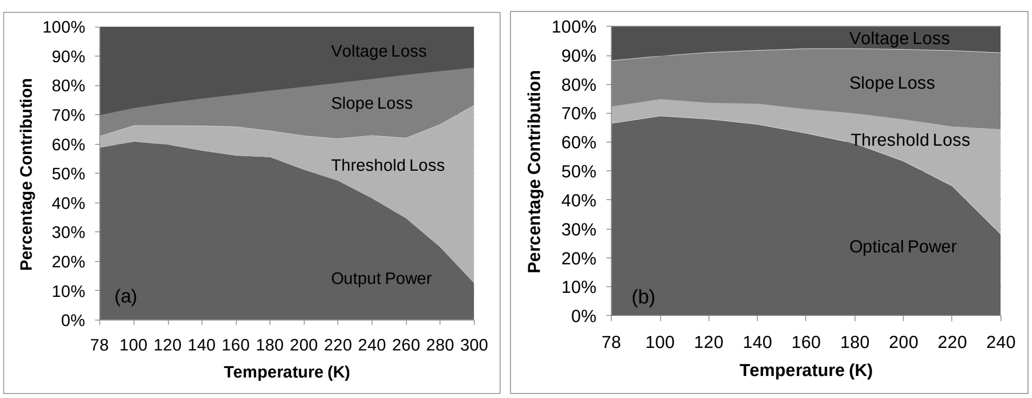

Fig. 1: Temperature dependence of main terms limiting efficiency for (a) the control design and (b) the experimental design with 1.5 mm cavity length. Measured at an injection current of 2 A.

2. Experiments and Analysis

Two diode laser structures are evaluated: a control structure based on a commercial high-power design optimized for high efficiency at room temperature, and an experimental design intended for optimization at 77K. The control structure utilizes the InP-based p-cladding while the experimental design utilizes $In_{0.90}Ga_{0.10}As_{0.24}P_{0.76}$ [4]. The lasers are grown on S-doped InP substrates by MOCVD. Isolation between the 200 µm wide laser stripes is provided by proton implantation. Bars are cleaved to 1.0, 1.5 and 3.0 mm cavity lengths and rear and front facets coated equivalently. Single emitters are cleaved and bonded junction-down to copper C-mounts with In solder. Testing occurs in an evacuated cryostat test chamber and power is measured using a thermopile.

The relative contribution of main terms limiting efficiency can be represented by their percentage contribution to the injected electrical power. Fig. 1(a) illustrates these terms in the control design at various temperatures. As shown, at cryogenic temperatures, slope loss and threshold current is greatly reduced, due to a dramatic reduction in non-radiative losses such as Shockley-Read-Hall and Auger recombination, as well as reduction in leakage current associated with thermionic emission of carriers from the quantum wells (QWs). However, the voltage defect (excess diode voltage drop beyond photon voltage) is greatly increased at low temperatures, affecting the overall conversion efficiency. The experimental design features a reduction of voltage defect at cryogenic temperature through increasing doping density, reducing the energy band offsets at the heterobarriers, and changing p-cladding materials to reduce dopant ionization energy. The improved voltage loss is shown in Fig. 1(b), reduced from 30% in the control design to ~10% in the experimental design. However, the slope loss remains relative large at cryogenic temperatures, mitigating the conversion efficiency gain through voltage improvement.

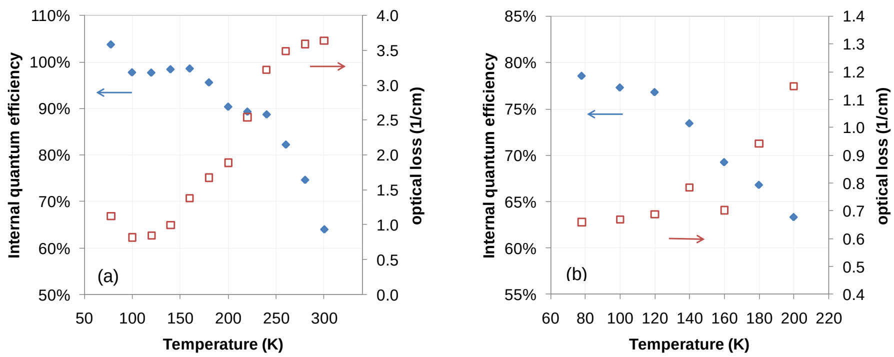

Fig. 2: Internal quantum efficiency (η_i) and optical loss (α_i) as a function of temperature for (a) control design and (b) experimental design, retrieved from cutback experiments.

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 cutback study). The extracted η_i and α_i at various temperatures are plotted in Fig. 2 for both the control and experimental 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 probably due to strong intervalence band absorption (IVBA) at QWs and optical waveguide. If a temperature-independent absorption coefficient is assumed [5], IVBA should be proportional to the free hole density, which follows Fermi function over temperature. The optical loss in Fig. 2(a) qualitatively follows such dependence, until saturates at low temperatures at losses related to the scattering loss and free carrier absorption within QWs. The optical loss in the experimental design has similar values to those in the control design at low temperatures [Fig. 2(b)], excluding it as the limiting factor to conversion efficiency. However, the internal quantum efficiency is below 80% even at 77K, indicating non-vanishing leakage current associated with thermionic emission of carriers. This is probably related to reduced band offset, as well as shallow QWs in the experimental design. A further improvement to the design of laser structure including the active region and waveguide could result in further optimization of the overall conversion efficiency.

3. Conclusion

In summary, the performance of two InP diode laser designs, optimized for room temperature and cryogenic temperatures, respectively, are studied at various temperatures. Analysis of the test data reveals how the major terms limiting efficiency evolve over temperature. Internal quantum efficiency and optical loss extracted from cutback study provide further information on conversion efficiency, limited by excess diode voltage and thermionic emission of carriers at cryogenic temperatures, indicating opportunities for further efficiency improvement.

4. References

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