Continuous Improvement of High-Efficiency, High-Power 800-980nm Diode Lasers at Spectra-Physics

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ABSTRACT

New-generation multi-mode 9xx mini-bars used in fiber pump modules have been developed. The epitaxial designs have been improved for lower fast-axis and slow-axis divergence, higher slope efficiency and PCE by optimizing layer structures as well as minimizing internal loss. For 915nm mini-bars with 5-mm cavity length, maximum PCE is as high as ~61% for 35W operation and remains above 59% at 45W.

For 808nm, a PCE of 56% at 135W CW operation has been demonstrated with 36%-fill-factor, 3-mm-cavity-length, water-cooled bars at 50°C coolant temperature. On passive-cooled standard CS heatsinks, PCE of >51% is measured for 100W operation at 50°C heatsink temperature. Leveraging these improvements has enabled low-cost bars for high-power, high-temperature applications.

Keywords: diode lasers, mini-bar, laser bar, power conversion efficiency, high power

1. INTRODUCTION

Laser diodes are key enabling components of high-power laser systems including a variety of diode-pumped solid-state (DPSS) lasers, fiber lasers and optical amplifiers, and are increasingly used in direct diode applications as well. Efficiency, power, and reliability are the primary performance metrics for high-power laser diodes. For the laser diodes in the 780-980nm wavelength band, PCE of 60-70% have been reported by several commercial suppliers. Continuous development is now shifting to the extension of high efficiency to high facet power density operation, high production yield and manufacturability, low-cost fiber-coupled package, and the associated reliability improvement.

Spectra-Physics has continued to improve the device performances operating in the range of 800-980nm [1-5]. The use of more capable epitaxial designs has become key to the improved operation. This paper will give an overview of recent progresses. These include the development of new-generation 9xx mini-bars used in fiber pump modules [6] and laser bars operating near 808nm at high junction temperatures.

2. LASER STRUCTURE DESIGN AND TECHNOLOGY

Spectra-Physics's laser diode technology is based on MOCVD-grown epitaxial wafers with optimized structures for high power levels, low internal losses, and low lateral and vertical far-field divergences. Low internal losses are clearly needed to maintain high differential quantum efficiency in long-cavity lasers (3-5mm), for which the electrical and thermal resistances are significantly decreased. Lower far-field divergences are crucial for obtaining high coupling efficiency with increased coupling tolerances. The details of these structures (e.g., material compositions, layer thicknesses, and doping profiles) are selected to ensure that manufacturability and reliability are not compromised.

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Standard wafer processing techniques are used to fabricate 5-emitter chips (a. k. a., mini-bars) and 10-mm-wide multi-emitter arrays (a.k.a., bars) from grown wafers. All mini-bars discussed in this work are bonded p-side-down on passively cooled CuW CT heatsinks with hard solder. All bars are bonded p-side-down with indium solder either on passively cooled Cu CS heatsinks or water-cooled, micro-channel Cu heatsinks.

3. NEW-GENERATION OF 9XX AND 880NM MINI-BARS AND BARS

3.1 9xx and 880nm Mini-bars

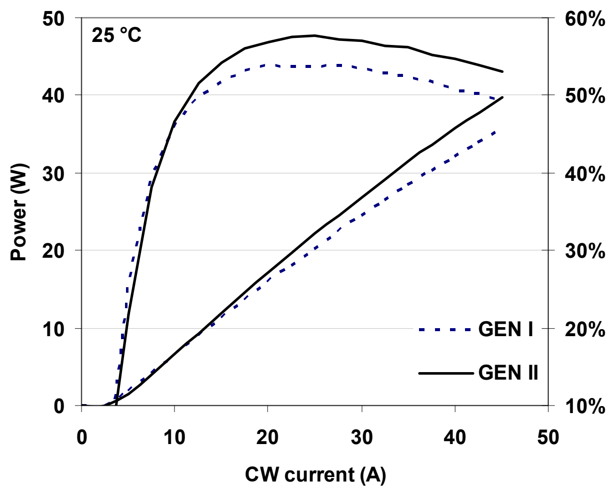

Fig. 1. P-I-PCE curves of mini-bars with old and new epi designs.

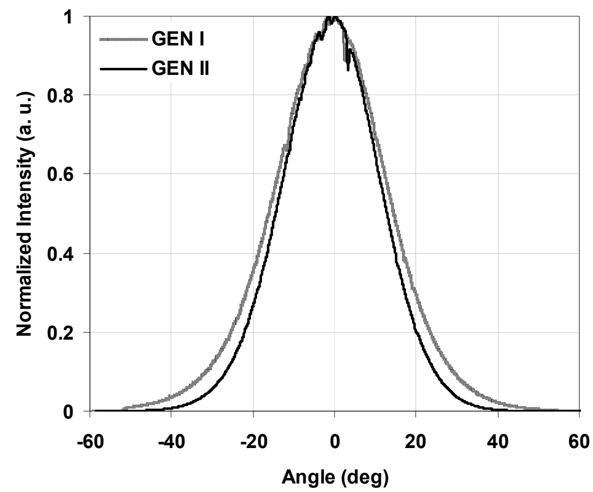

Fig. 2. Fast-axis divergences of old and new epi designs.

Multi-emitter chips, referred to as mini-bars, are assembled on platforms traditionally restricted to single-emitter devices. Such devices have emerged as key to the reduction of both the cost and size of diode-laser sources in high-volume applications. Figure 1 compares the typical performance of two-generation 980nm mini-bars recorded at 25°C heatsink temperature. The device geometry is same, and cavity length is 5-mm long. The new-generation devices (Gen II) operate with an initial slope efficiency of 1.06 W/A, 10% higher than previous generation (Gen I). The maximum PCE (at ~23W) is improved from 54% to 58%. These improvements are mainly due to the reduced internal loss of the new epitaxial design.

Besides optimizing the electro-optical performance, the fast-axis emission divergence of the devices is very important. Lower divergence out of the laser not only improves the coupling efficiency but also allows adjustment of the fast-axis collimation lens with more tolerance at a longer working distance. As shown in Figure 2, the fast-axis divergence FWHM is reduced from 31° to 27°, and the divergence for 95% power inclusion is reduced from 57° to 47°. The fast-axis divergence reduction is associated with the near-field spot size (FWHM) increase by approximately 40%, which significantly increases the threshold for catastrophic optical mirror damage (COMD). From the statistical comparison, the burn-in yield of the new design is clearly higher than the old designs.

Another lasing parameter that has benefited from the new epitaxial design is slow-axis divergence. Unlike the fast-axis divergence which is stable with operating current, slow-axis divergence is known to broaden at higher operating currents. This becomes the limiting factor to sustain high coupling efficiency into low numerical aperture at high power operation, and results in reduced brightness of pumping power. The slow-axis divergence is mainly dependent on stripe geometry design as well as epitaxial layer designs. Figure 3 compares the dependence of slow-axis divergence (95% power inclusion) of the old and new epitaxial designs as functions of operating power with same stripe geometry. At 25W operating power, the new design (Gen II) has a divergence of 7.8°, compared to the 8.9° of the old design (Gen I).

In addition, the divergences of the new design deteriorate more slowly with output power. Such behavior ensures high coupling efficiency at high driving level and the feasibility to scale to higher power.

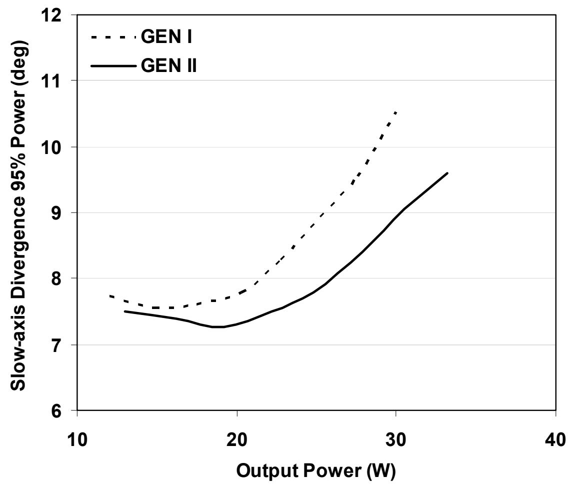

Fig. 3. Evolution of slow-axis divergences with CW power

The new epitaxial design can be extended to the applications for 880, 915, and 940nm. For example, the performance of an 880nm min-bar with 5mm cavity length is shown in Figure 4. The power reaches almost 40W at 45A, and the maximum PCE is >56% at ~29W. The threshold current is ~8A and the slope efficiency is 1.15W/A. Typical spectra with 2.2nm FWHM is shown in Figure 5. Figure 6 is the temperature-dependent performance of a 915nm mini-bar, again with 5mm cavity length. The device was tested up to 45 A at heatsink temperatures from 15 to 55 ˚C. The maximum PCE at 35W is 61% at 15°C and remains above 59% at 45W. Even at 55 °C, the maximum efficiency is still over 53%. Emitting spectra at 25°C at various operating currents are presented in Figure 7. The average centroid wavelength shift is 0.24 nm/A. The FWHM and FW10% of the spectrum at 31.5 W operating conditions are typically 2.4 and 4.4nm, respectively, a signature of excellent thermal and stress uniformity among individual emitters, in spite of their very long cavity length.

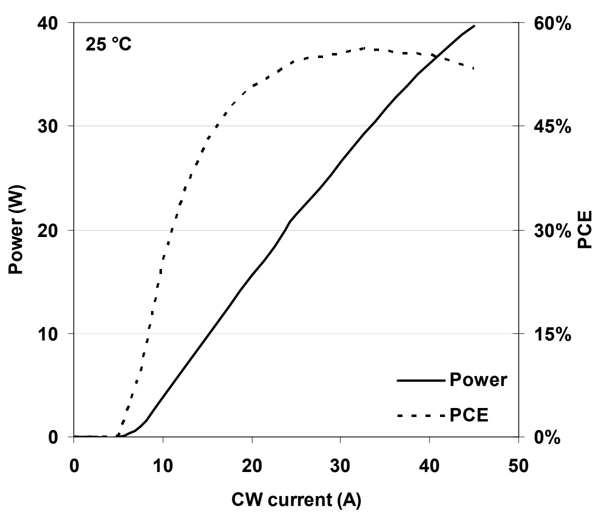

Fig. 4. P-I-PCE curves of an 880nm mini-bar.

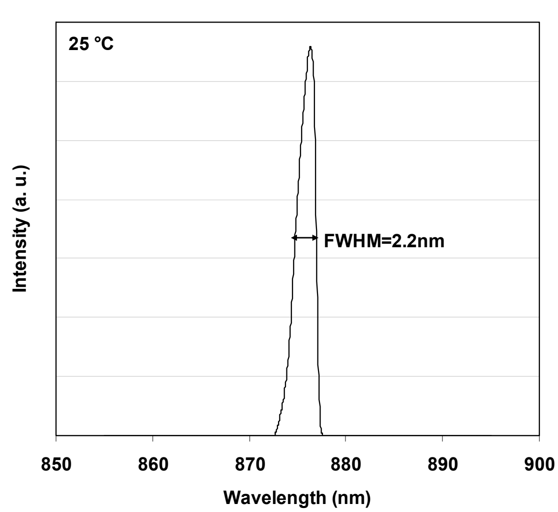

Fig. 5. Lasing spectra of an 880nm mini-bar.

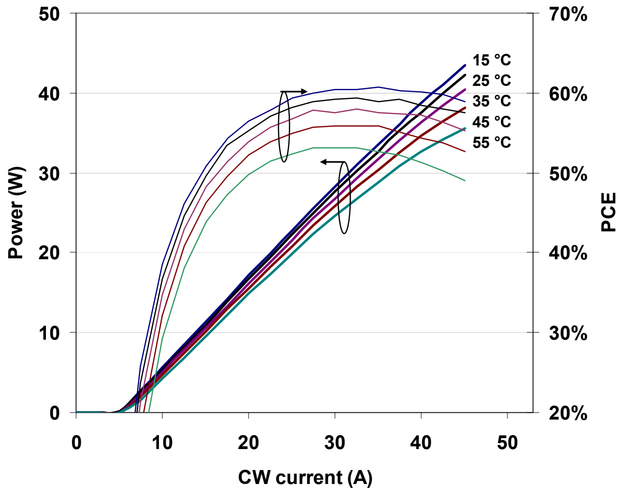

Fig. 6. P-I-PCE curves of a 915nm mini-bar.

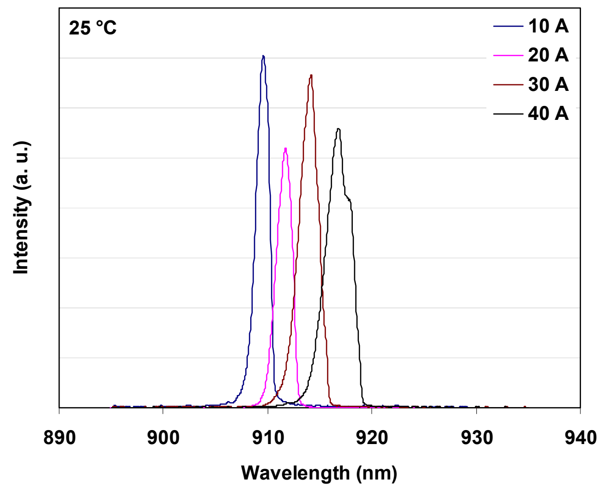

Fig. 7. Lasing spectra of a 915nm mini-bar at different currents.

3.2 9xx 1-cm-wide CS bars

Figure 8 summarizes typical CW characteristics of a 980nm bar with Gen II epitaxial design, consisting of 19 emitters (each 135-µm wide and 2-mm long) with 500 µm center-to-center separation, on a passive-cooled CS heatsink at 25°C. The bar is running at 70W with a PCE of 64%. The threshold current is 8A, equivalent to a threshold current density of 155 A/cm^2. The slope efficiency is 1.15 W/A. We reported ~70% PCE from 9xx CS bars with an earlier design which has lower turn-on voltage and series resistances [1].

For pumping customers, lasing spectrum profiles with relatively narrow linewidth and single peak are crucial for the optical power density delivered to the target to increase absorption efficiency. The stability of spectrum profiles with operating currents and temperatures is also important. Figure 9 shows typical emission spectra of 50A measured for CS bars at different heatsink temperatures.

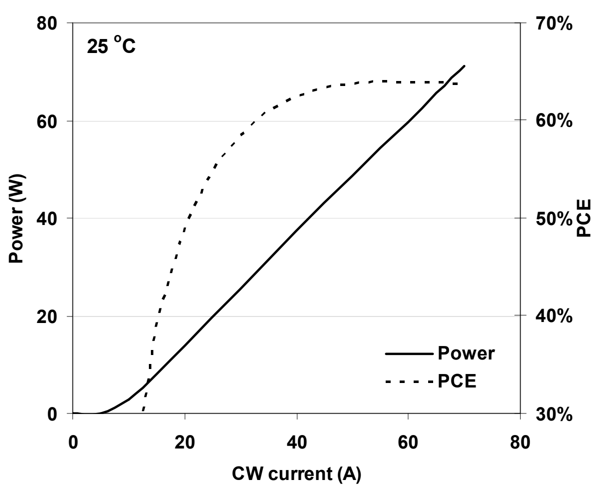

Fig. 8. P-I-PCE curves of a 976nm CS bar.

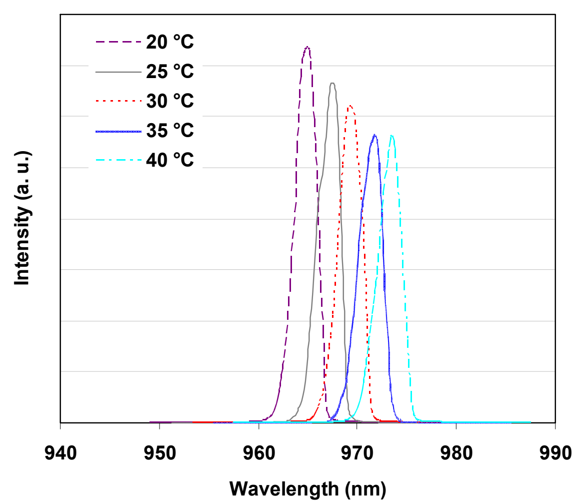

Fig. 9. Temperature-dependent lasing spectra of a 976nm CS bar.

4. 808NM BARS FOR HIGH-TEMPERATURE APPLICATIONS

Simplified cooling is an important aspect of high-power diode-laser operation, especially for severe environmental conditions and mobile platforms. High-efficiency performance is compatible with both operation at elevated temperatures and operation with reduced cooling requirement. The efficiency of 808nm lasers is generally lower than 9xx laser, largely due to its higher transparency current density and operating voltage. We have reported 65% PCE at 80W and 25°C water-coolant temperature from 808nm water-cooled laser bars with relatively short cavity length and low fill factor [5]. For higher power and operation temperature, temperature sensitivity and thermal resistance of the laser bars have to be improved.

Figure 10 shows the performance of 808nm passively cooled CS bars (40-emitter, each 90-µm and 3-mm cavity) with improved epitaxial design (Gen II) which was developed recently for improved efficiency and high power (>100W) at very high junction temperatures. Gen I design is an earlier design used to demonstrate 65% PCE [5]. The bars were tested from 80 to 140A at 50°C heatsink temperature. At 120A, the output power is increased from 86W to 101W, meanwhile the PCE is improved from 41% to 48%. The epitaxial improvements have focused on optimizing dopant distribution for reduced internal loss and enhanced carrier confinement for higher characteristic temperatures. Relatively long cavity is used for better thermal conduction to heat sink. The thermal resistance is measured to be 0.4°C/W. The junction temperatures are calculated to be 98 and 93°C at 120A operation for Gen I and II, respectively, which is even ~10°C higher than those of 1-cm-wide high-fill-factor bars we used to demonstrate >1kW CW power per bar [2,3].

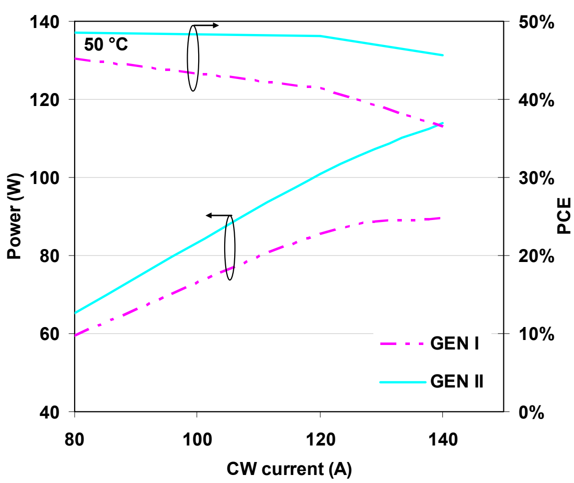

Fig. 10. P-I-PCE curves of passively-cooled 808nm CS bars.

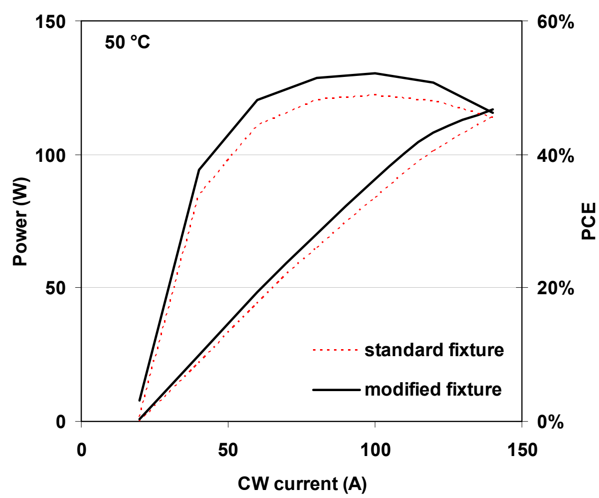

Fig. 11. P-I-PCE curves of 808nm CS bars with different test fixture.

For passively cooled CS bars, the thermal interface between CS heatsink and testing fixture is crucial. Heat exchanging at this interface have been optimized to reduce the overall thermal resistance. Figure 11 compares the performance of a CS bar tested with standard testing fixture and modified testing fixture. The bar geometry is same as that of Figure 11. The modified fixture applies larger contact pressure, and therefore has better thermal conductivity to the cooling plate underneath. At 120A, the output power is increased from 101W to 108W, and PCE is improved from 48% to 51%. The junction temperature is lowered from 98 to 88°C. The maximum PCE of >52% occurred at 90W with modified fixture.

To bond same 1-cm bars of GEN II in Fig. 10 on water-cooled micro-channel heatsinks, the performance can be greatly improved. An example of Gen II design is presented in Figure 12. The CW output power, measured at 140A with a water coolant temperature of 50°C, is 135W with a PCE of 56%. The maximum PCE of 57% is measured at 120A. The initial slope efficiency before the onset of thermal rolling is 1.20 W/A.

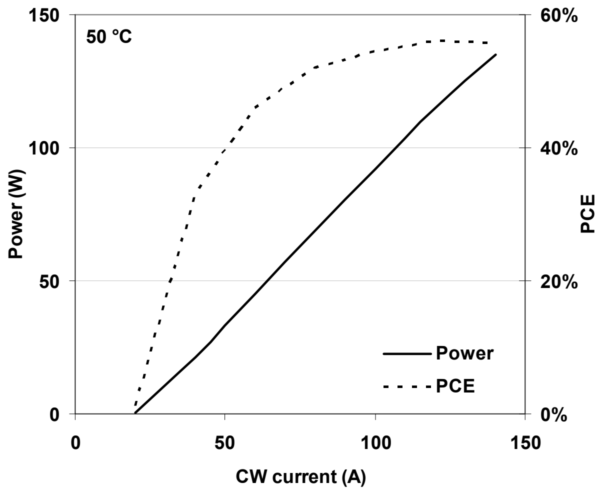

Fig. 12. P-I-PCE curves of an 808nm water-cooled bar.

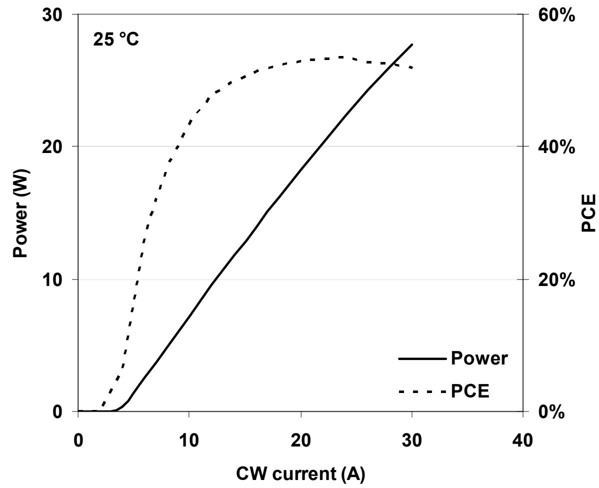

Fig. 13. P-I-PCE curves of an 808nm mini-bar.

The new design is also good for mini-bar applications. Figure 13 summarizes typical CW characteristics of a Gen II mini-bar. It consists of 5 emitters (each 90-μm wide and 3-mm long), bonded on a CT heatsink and tested at 25°C. The maximum PCE is in excess of 53% and only slight thermal rollover is observed in CW operation up to 30 A (corresponding to 27.7W).

5. CONCLUSION

The performance of diode lasers in the wavelength range 800-980nm continues to improve with advances in epitaxial designs and thermal management. In addition to the PIV performance improvement, fast- and slow-divergences as well as the lasing spectra profiles have been substantially improved for 880-980nm wavelength range. The stress lifetest and long-term lifetest are ongoing. A new-generation low-cost 808nm bars for high-power, high-temperature applications is introduced.

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