Advances in high-brightness semiconductor lasers

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ABSTRACT

We present recent advances in high power semiconductor laser bars and arrays at near infrared and eye-safe wavelengths. We report on increased spectral brightness with internal gratings to narrow and stabilize the spectrum and increased spatial brightness in multimode and single mode devices. These devices have the potential to dramatically improve diode pumped systems and enable new direct diode applications.

Keywords: Diode, laser, semiconductor, bar, stack, array, single mode, visible

1. Near infrared wavelengths: High Spatial Brightness

The maximum optical output power of laser diodes in the 800 - 1000 nm regime is often limited by catastrophic optical damage (COD). COD occurs when the facet temperature reaches the melting point of the semiconductor material. The two foremost causes of facet heating are optical absorption of the laser light near the facet and non-radiative recombination of electron-hole pairs at the surface states of the cleaved facet. Inserting a high bandgap, current blocking region at the facet can greatly reduce the optical absorption and facet current leakage. QPC has developed and optimized a proprietary high power non-absorbing mirrors (NAMs) technology called Brightlase™. The NAM is created in InAlGaAs laser diodes using an epitaxial regrowth process to produce a region near the facet that is both optically non-absorbing and electrically nonconductive. The inclusion of the NAM triples the COD power and greatly improves the reliability of the laser diode. As shown in Figure 1, the active layer is removed near the facet, and replaced with an epitaxially regrown layer of wide-bandgap Aluminum Gallium Arsenide. This layer isolates the active layer from surface states, and is highly transparent to the laser emission from 800 to 1000nm.

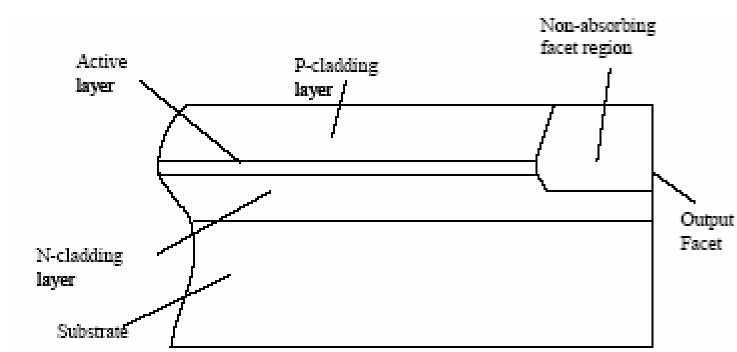

Figure 1: Side view of semiconductor laser showing BrightLase NAM region

Figures 2 and 3 show power versus current and the output spectrum of 976 nm conduction cooled fiber coupled modules that utilize the BrightLase® technology. More than 55 Watts from a 100 micron fiber with 0.22 numerical apeture is achieved, and more than 110 Watts is shown from a 400 micron 0.22 NA fiber.

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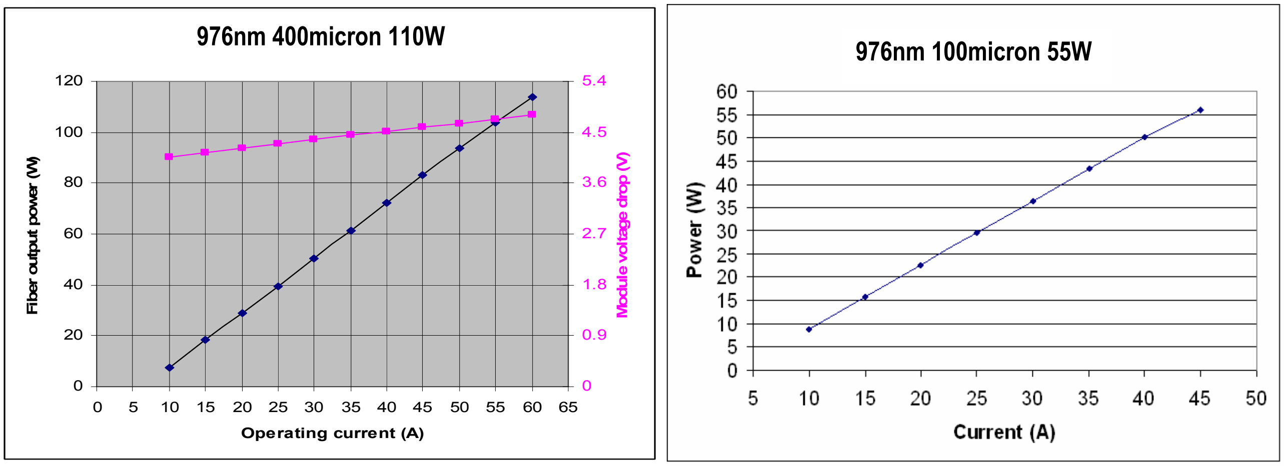

Figure 2: 976 nm conduction cooled module, power versus current

In addition to 976 nm, QPC has demonstrated fiber coupled modules at 808 nm with more than 45 Watts from a 100 micron fiber, 0.22NA. Because of the inclusion of the NAM, fiber coupled modules can be pulsed to higher peak power than typical fiber coupled modules. For example, Figure 3 shows QCW performance over 90W peak power from 400 micron, 0.22 NA fiber coupled module with 300 microsecond pulse width, with an energy of 28 mJ/pulse, at 100 Hz.

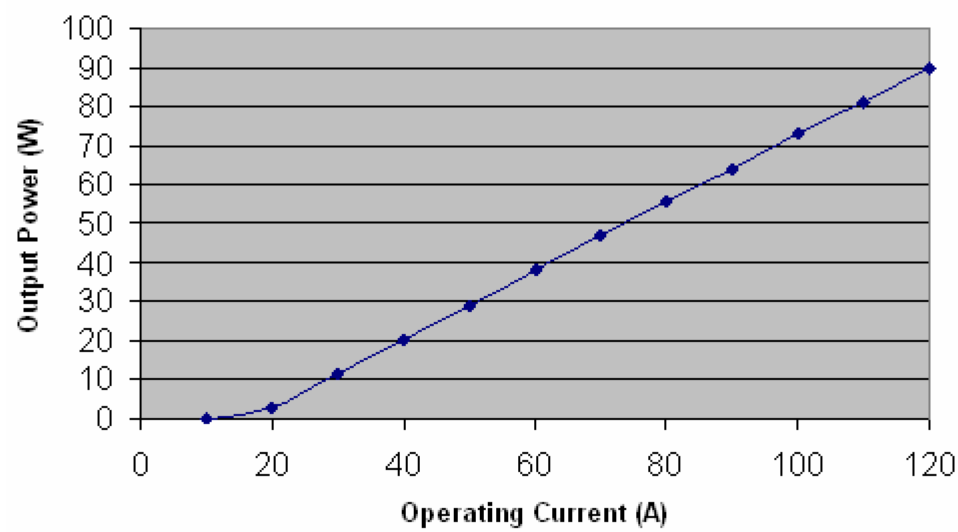

Figure 3: 808 nm conduction cooled fiber coupled module with 100 Watts peak power output

2. Near IR Wavelengths: High Spectral Brightness

Diode lasers in the 780 nm to 1000 nm regime are used in a variety of applications including pumping fiber and solid state lasers, and direct diode materials processing, defense, and medical applications. High power diode lasers are conventionally formed by inserting a gain-producing active stripe into a resonant cavity formed by reflective facets at each end of the laser. Aside from defining the periodic “comb” of resonant frequencies, this Fabry-Perot cavity provides essentially no wavelength control. Wavelength of emission is instead controlled by the gain spectrum of the semiconductor used as the active layer. Unfortunately, this gain spectrum is “flat” (with width ~ 20 nm), and strongly temperature dependent. As a result, the output spectrum is broad, particularly at high power fluxes, and highly dependent on the operating temperature, typically changing by 0.3 nm per ºC. For high power devices, external methods have been used to achieve high spectral brightness such as the use of using seed lasers in MOPA designs[1], the use of external lenses and bulk gratings[2], or volume Bragg gratings[3]. These external approaches require sensitive alignment techniques, costly additional lasers and or optics, and specially designed coatings. Internal DFB or DBR gratings similar to those used in telecom lasers would offer an on-chip solution, but, unfortunately, it is not trivial to adopt this approach for high power diode lasers since they are multi-mode and more difficult to lock.

QPC has recently demonstrated high power semiconductor lasers at 795 nm, 808 nm, 976 nm, 1040 nm, 1064 nm, 1470 nm, 1532 nm, and 1550 nm that include an internal grating technology called BrightLock™. The grating, written directly into the device, provides feedback to narrow the optical spectrum, reduces the wavelength-temperature sensitivity, and ensures that the device operates at the desired wavelength. These devices can dramatically improve performance and reduce cost in diode pumped laser systems and direct diode applications such as medical imaging and Raman spectroscopy. The gratings are written holographically at the wafer level, and Figure 4 shows a typical atomic force microscope image.

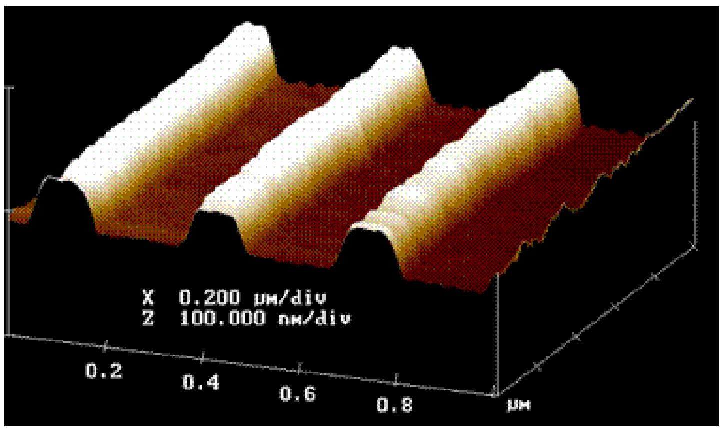

Figure 4: AFM image of internal gratings

Performance of fiber coupled modules at 976 nm with BrightLock™ internal Bragg gratings show unique light-current characteristics and emission spectrum as function of current and temperature as compared to standard devices. The spectra are extremely narrow near threshold (<0.1 nm). At output powers up to 340W, the devices are much narrower with typical widths in the 0.1 to 0.4 nm FWHM compared to Fabry-Perot lasers with1-5 nm FWHM. At 20 ºC, the emission spectrum remains locked to grating and narrow spectrum to > 340W and over a broad current range and >40 deg C temperature range. The wavelength dependence on temperature is <0.08 nm/ºC, 3-4 times smaller than for a Fabry-Perot laser. In Figure 5, the power versus current performance for conduction cooled fiber coupled module. The output spectrum is <0.4 nm FWHM and the wavelength temperature coefficient is <0.8 nm per degree Celcius.

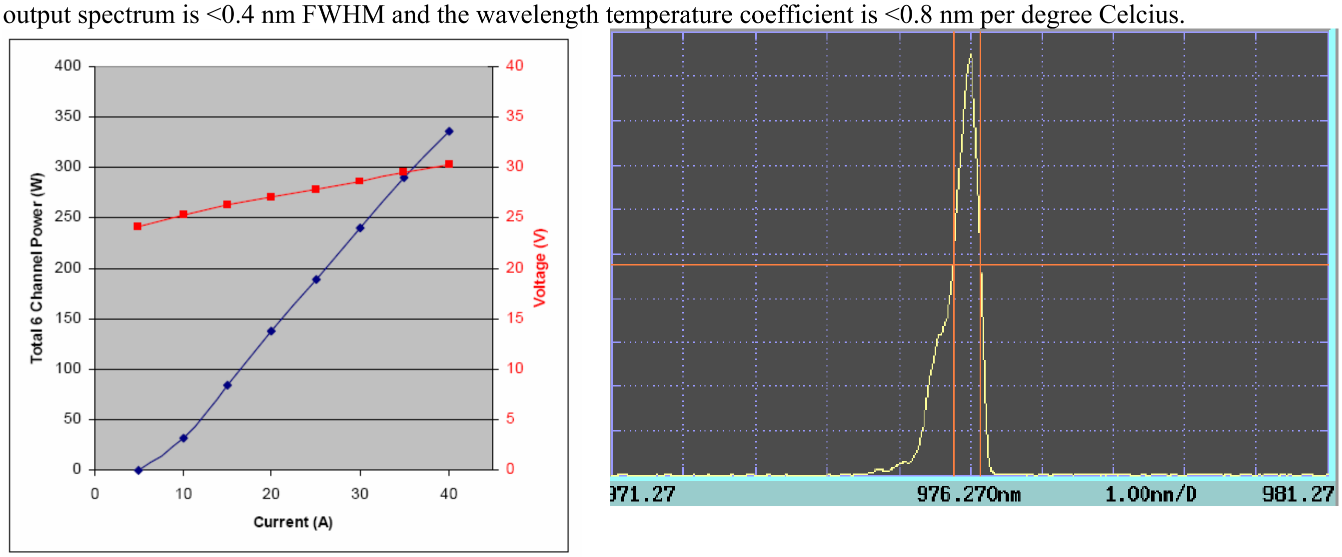

Figure 5: 976 nm fiber coupled module with internal grating stabilization

3. Near IR Single Mode Lasers: High Spatial and Spectral Brightness

In addition to the multimode devices described above, we have developed high power single frequency, single transverse mode devices at 1040 nm for fiber laser seeding and direct applications in the eye-safe regime. Tapered devices have been demonstrated previously, but achieving higher power levels with near diffraction-limited performance has shown to be challenging because of filamentation at relatively low powers and poor yields due to beam quality deterioration at high powers. Our device design is a two section oscillator-amplifier device consisting of a narrow waveguide section and a tapered gain section. In our design, the beam in the narrow waveguide distributed feedback (DFB) section is laterally confined by a single-mode waveguide which produces a single frequency stable beam. A buried heterostructure (BH) single mode waveguide is used to effectively act as a mode filter. This beam is fed into the tapered gain section, where the mode is allowed to freely diffract and be amplified by a tapered electrical contact. See Figure 6 for a schematic.

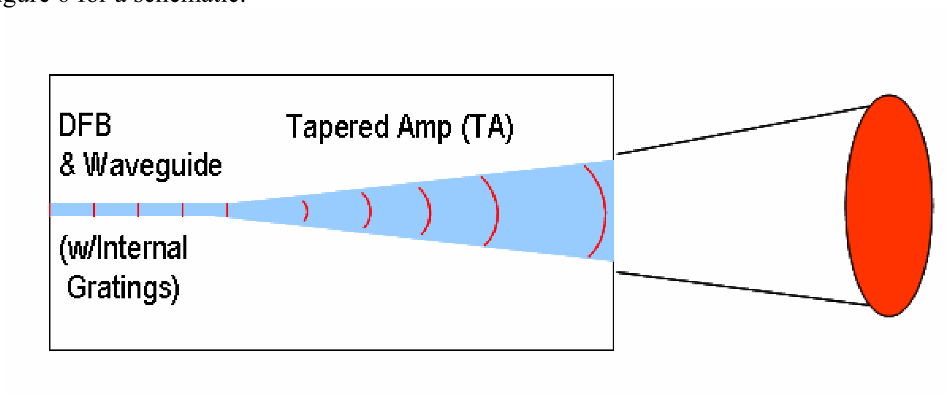

Figure 6: Schematic of single frequency single mode MOPA device

We have recently demonstrated >9W with single frequency and single transverse mode operation at 1064 nm. The efficiency is >50% at 3 Watts and then decreases due to thermal limitations of the mount. Figure 7 shows the CW power versus current curve for such a device with a constant 700mA in the oscillator section.

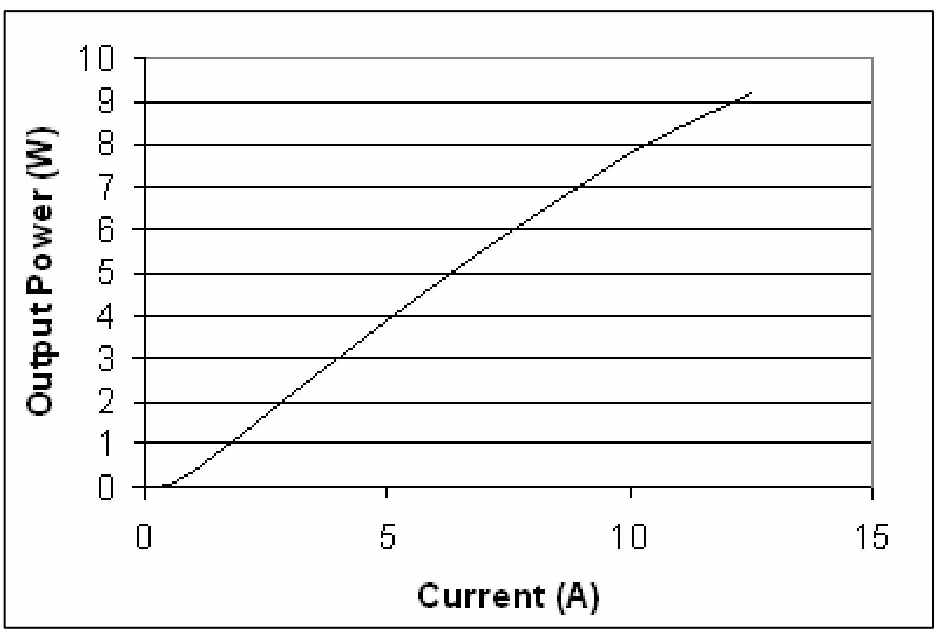

Figure 7: Power versus current in the amplifier section for 1064 nm single frequency single mode MOPA device.

The devices operate with single longitudinal mode and more than 35dB of suppression was observed. Figure 8 shows the spectrum (log scale) of the device.

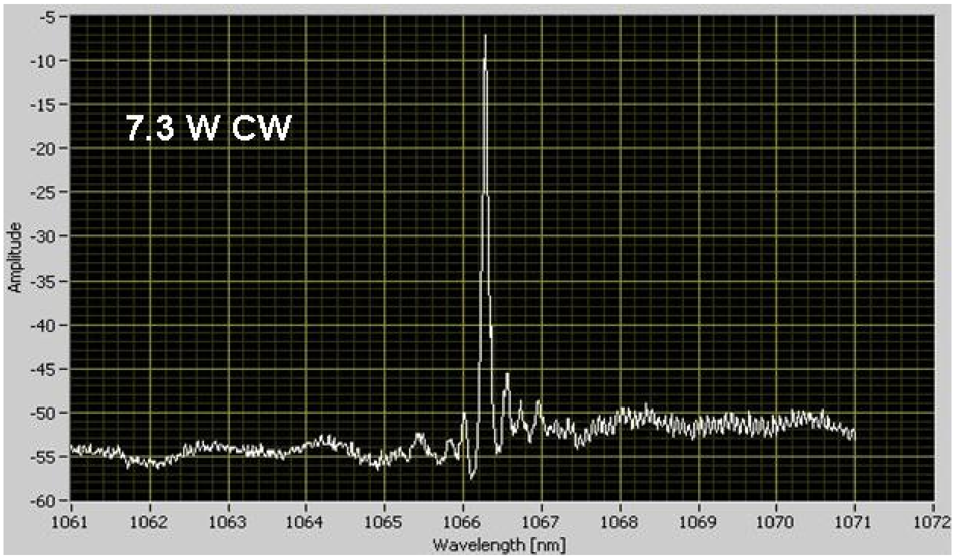

Figure 8: Spectrum for 1064 nm single frequency single mode MOPA device (log scale).

The single mode devices are ideally suited for low cost frequency doubling to the visible. Figure 9 below shows a typical frequency doubling technique to generate 532 nm. Over 600 mW of 532 nm has been demonstrated with < 5 Watt input at 1064 nm.

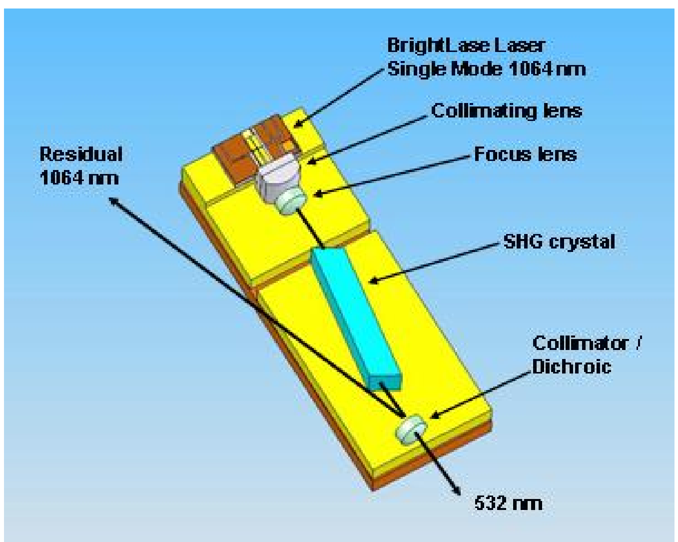

Figure 9: Layout for frequency doubling of 1064 nm single frequency single mode MOPA device.

4. Eye-safe Wavelengths: Advances in Spectral and Spatial Brightness

Diode lasers in the 1400 nm to 1600 nm regime are used in a variety of applications including pumping Er:YAG lasers, range finding, materials processing, and aesthetic medical treatments. In addition to the compact size, efficiency, and low cost advantages of traditional diode lasers, high power semiconductor lasers in the eye-safe regime are becoming widely used in an effort to minimize the unintended impact of potentially hazardous scattered optical radiation from the laser source, the optical delivery system, or the target itself.

QPC has developed high power fiber coupled modules at 1532 nm with internal grating based on conduction cooled bars. Figures 10 and 11 below show the power versus current and output spectrum of a 1532 nm fiber coupled module with 400 micron, 0.22 NA output operating at 100 Watts at ~50 A. The output spectrum exhibits a spectral width less than 1.2 nm wide, roughly 5-10 times narrower than a similar Fabry-Perot without an internal grating.

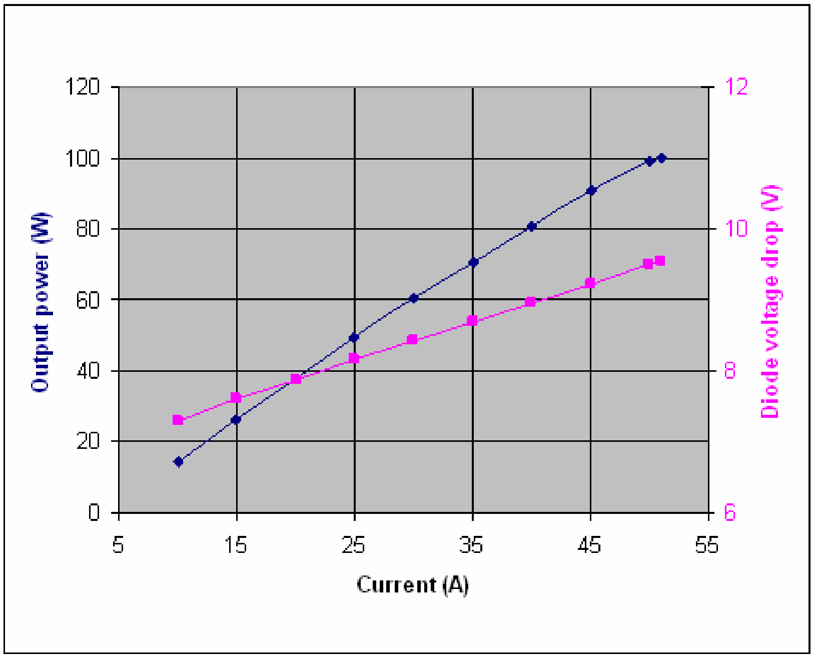

Figure 10: 1532 nm bar with internal grating stabilization, power versus current performance

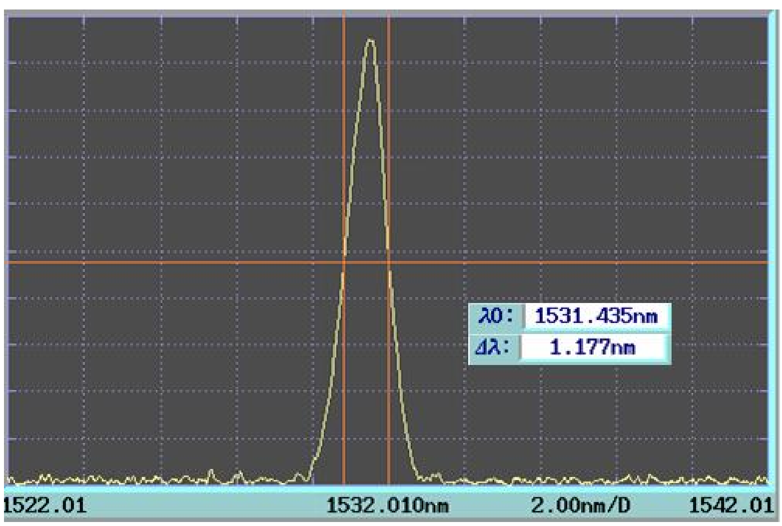

Figure 11: 1532 nm bar with BrightLock™ internal grating stabilization showing <1.2 nm FWHM spectrum.

Actively cooled stacks were also fabricated using similar semiconductor lasers. Below is performance data showing > 300 W at 1532 nm from a 10 bar water cooled stack. The spectral width is 1.9 nm FWHM.

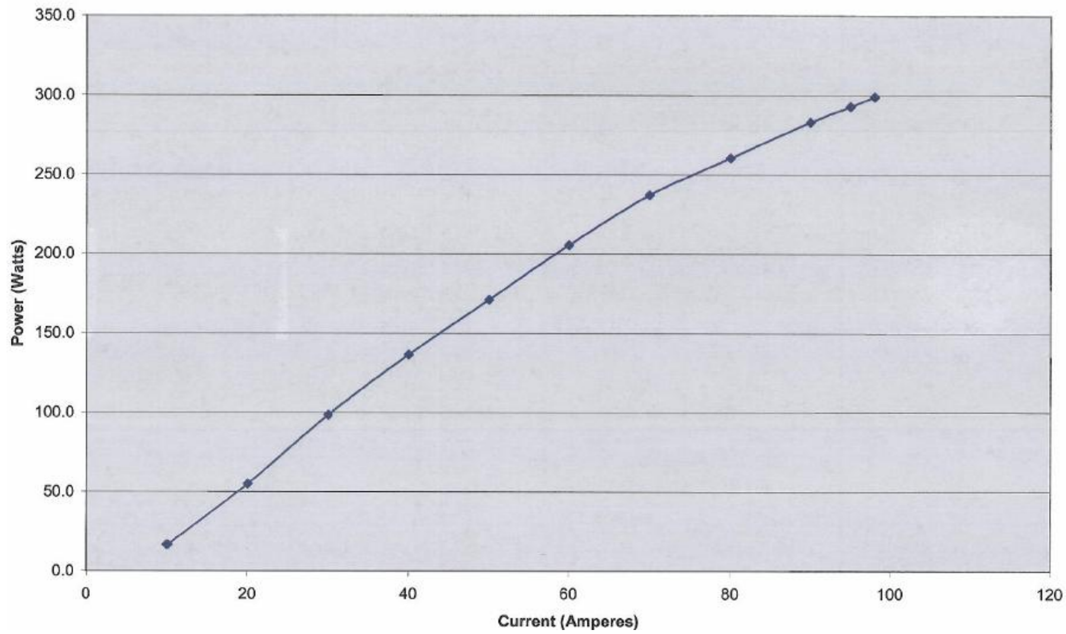

Figure 12: 1532 nm 10 bar water cooled stack showing 300 W CW. The spectral width was measured to be 1.9 nm FWHM.

Additionally, QPC has developed a 1550 nm single mode single frequency diose laser using a similar approach to the device shown in Figure 6. The device outputs >1.5 Watts at 1550 nm CW, and QPC has recently tested the device in pulse mode. Below is performance data showing >25 W peak power with 10 nsec pulses and >15 W peak power with 60 nsec pulses with a 500 kHz repetition rate.

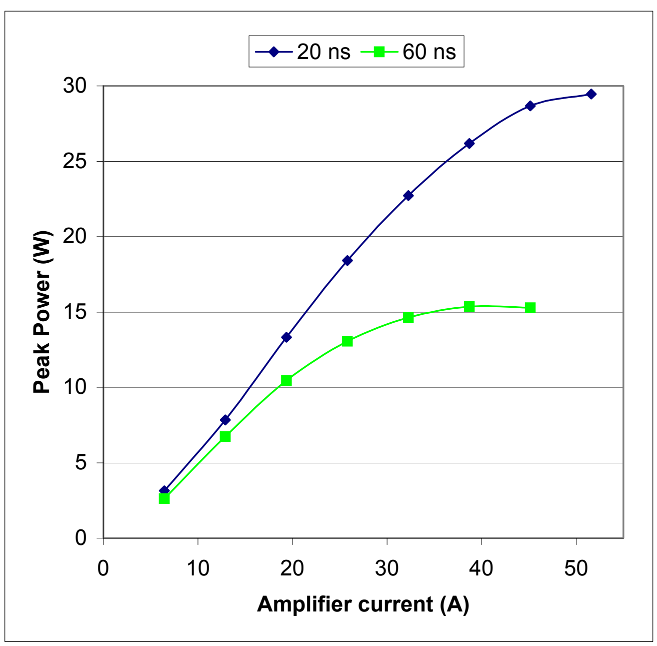

Figure 13: 1550 nm single mode single emitter showing >25 W peak power with 10 nsec pulses and >15 W peak power with 60 nsec pulses.

5. Conclusions

The recent advances in high brightness, high power semiconductor laser technology include >55 Watts at 976nm from a 100 micron fiber coupled module and >110 Watts from a 400 micron fiber suitable for fiber laser pumping. Additionally, QPC has demonstrated >9W single mode 1064nm lasers which can be frequency doubled with high efficiency. Utilizing internal Bragg gratings, >340W was demonstrated at 976 nm with <0.5 nm FWHM spectral width from a fiber coupled module. In the eye-safe regime, >100 Watts was demonstrated at 1532 nm with < 1.6 nm FWHM spectral width from a fiber coupled module with 400 micron output.

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REFERENCES

1. Wolfring, B.J.; Kaenders, W.G.; Quantum Electronics and Laser Science Conference, 1999. 23-28 May 1999 Page(s):63 – 64, “Injection-locked diode laser system delivering up to 200 mW tunable single-mode output at 685 nm”
2. Yiou, S.; Balembois, F.; Georges, P.; Huignard, J.-P.; Lasers and Electro-Optics Europe, 2003. CLEO/Europe. 2003 Conference on 22-27 June 2003 Page(s):157, “Narrow beam divergence of laser diodes with a Bragg grating in external cavity”
3. Ciapurin, I.; Smirnov, V.; Venus, G.; Glebova, L.; Rotari, E.; Glebov, L.; Lasers and Electro-Optics, 2004. (CLEO). Conference on Volume 1, 16-21 May 2004 Page(s):3 pp. vol.1, “High-power laser beam control by PTR Bragg gratings”
4. “High Reliability, High Power InGaAs/AlGaAs 980 nm Distributed Feedback Lasers with Nonabsorbing Mirrors”, Lammert, R.M., Ungar, J.E., Oh, S.W., Osowski, M.L., Bar Chaim, N., LEOS ’99, IEEE Lasers and Electro-Optics Society 1999 12th Annual Meeting vol .1 p194
5. Yiou, S.; Balembois, F.; Georges, P.; Huignard, J.-P.; Lasers and Electro-Optics Europe, 2003. CLEO/Europe. 2003 Conference on 22-27 June 2003 Page(s):157, “Narrow beam divergence of laser diodes with a Bragg grating in external cavity”
6. Ciapurin, I.; Smirnov, V.; Venus, G.; Glebova, L.; Rotari, E.; Glebov, L.; Lasers and Electro-Optics, 2004. (CLEO). Conference on Volume 1, 16-21 May 2004 Page(s):3 pp. vol.1, “High-power laser beam control by PTR Bragg gratings“
7. D.W. Nam et al., IEEE Photon. Tech. Lett., 5, 281 (1993).