Advances in high brightness semiconductor lasers
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ABSTRACT
We review recent advances in high power semiconductor lasers including increased spectral brightness, increased spatial brightness, and reduced cost architectures at wavelengths from the near infrared to the eye-safe regime. Data are presented which demonstrate both edge emitter devices and high power surface emitting 2-dimensional arrays with internal gratings to narrow and stabilize the spectrum. Diodes with multimode high spatial brightness and high power single mode performance in the 808 and 976nm regime are described, and advances in high power bars at eye-safe wavelengths are presented. These devices have the potential to dramatically improve diode pumped systems and enable new direct diode applications.

Keywords: Diode, laser, semiconductor, bar, stack, array

1. Introduction
Conventional edge emitting high power diode lasers have been used in printing, defense, medical, and materials processing because of their compactness, low cost per Watt-hour, and excellent electrical to optical efficiency. While these high power diode lasers are broadly accepted for low brightness applications, their use has been limited due to the low spatial and spectral brightness performance, costly power scaling, and limited range of emission wavelengths. In particular, the spatial beam quality from high power diode lasers is a factor of 10-20 times lower than non-diode lasers such as gas, solid state, or fiber laser counterparts. Moreover, the spectral output of conventional diode lasers is typically an order of magnitude wider than these non-diode systems and is inadequate for efficient wavelength conversion or other pumping applications requiring narrow linewidth. Power scaling is achieved by combining the output of individually mounted bars, the cost of which scales linearly or superlinearly with power. Finally, the range of wavelengths available commercially from high power conventional diode lasers has mainly been limited to broadband emission in the near infrared regime of 800 nm to 980 nm.

We report here on semiconductor lasers with reduced linewidth, increased spatial brightness, low cost scalability to high powers and high manufacturing volumes, and output wavelengths ranging from 800 nm to the eye-safe regime. Our motivation is to enable a new class of pumping and direct diode applications with increased working distance, improved range, reduced spot size, reduced time on target, broad wavelength range, and improved system throughputs while maintaining the advantages of conventional diodes lasers such as device compactness, low cost per Watt-hour of output, and excellent electrical to optical efficiency.

2. Advances in spectral brightness
The most common application of semiconductor lasers is to pump the media of solid-state and fiber laser systems. The solid-state laser creates an output which has higher spatial brightness and a narrower spectrum. Increasing the spatial brightness and spectral accuracy of the pump diode enables the laser system designer to improve the laser system compactness, efficiency, power, and beam quality while at the same time reducing thermal management cost in the system. Additionally, scientific and medical pumping applications such as Raman spectroscopy and enhanced magnetic resonance imaging also require narrow semiconductor laser emission carefully matched to the center wavelength, spectral width and output power requirements of the atom or molecule being manipulated or examined.

2.1. Advances in spectral brightness: single emitter with internal Bragg gratings
Spectrally narrowing or locking of the output of single-mode diode lasers with an internal Bragg grating has been demonstrated previously in the low power regime. Internal diffraction gratings are widely used for wavelength control in low power InGaAsP single-mode telecommunications lasers at 1310 and 1550 nm. These have 3 times lower
wavelength dependence on temperature (0.08 nm per °C) and very narrow spectra. Unfortunately, it is not trivial to adopt this approach for high power short wavelength (<1000 nm) lasers because AlGaAs gratings are more difficult to epitaxially embed than InGaAsP, grating periods are much smaller, and high power stripe lasers are multi-mode and more difficult to lock. 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 characteristic 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 °C. For high power devices, external methods have been demonstrated such as the use of using seed lasers in MOPA designs, the use of external lenses and bulk gratings, or volume Bragg gratings. These external approaches require sensitive alignment techniques, costly additional lasers and or optics, and specially designed coatings. Quintessence Photonics has recently demonstrated high power single-stripe lasers at 808 nm and 980 nm that overcome these problems by including an internal grating acting as a distributed Bragg reflector that provides feedback, determines the oscillation frequency, and ensures that the emitter operates at the desired pump wavelength. In figure 1 and 2, we present results of a 980 nm 100 um single emitter. The power versus current performance shows 45% power conversion efficiency at 3.5W operation, and the output spectrum is ~0.2 nm FWHM.

![Figure 1](image1)

![Figure 2](image2)
Figures 3 and 4, respectively, show the structure and output spectrum of an 808 nm 100 µm wide stripe laser operating at over 3 Watts on a C-mount. The output spectrum is taken at 3A and 20 °C and is less than 0.3 nm wide, many times narrower than a similar Fabry-Perot.

Typical performance of the devices with internal Bragg gratings show unique light-current characteristics and emission spectrum as function of current and temperature as compare to standard devices. The 808 nm data are discussed in particular here, and the 980nm performance is quite similar. The 808 nm spectra are extremely narrow near threshold (<0.1 nm). At output powers up to 3W, the devices are much narrower than Fabry-Perot lasers with typical widths in the 0.1 to 0.3 nm regime compared to 1-2.5 nm for a Fabry-Perot. At 20 °C, the emission spectrum remains locked to grating and narrow spectrum to > 3.5 W and over a range of 2 to 5.5 A. The devices remain stabilized from temperatures 10 to 30 °C at fixed current (3A). The wavelength dependence on temperature is ~0.07 nm/°C, 3-4 times smaller than for a Fabry-Perot laser. Threshold current for these devices are higher (~1 A versus 0.5 A) and slope efficiencies are slightly lower (0.85 W/A versus 1 W/A) than non-Grating lasers. We believe that the lower efficiencies are not fundamental, and that as the grating design is iterated, optimization is possible.

2.2. Power scaling of high spectral brightness output: 2D surface emitting arrays with internal Bragg gratings

High power diode arrays are typically constructed by stacking micro-channel cooled linear bars to form two-dimensional laser arrays. For systems requiring portability, compactness, low cost, or high reliability, large scale pump stacks of individually mounted bars pose significant challenges. They are prohibitively expensive because each bar must be individually cleaved, coated, tested, and mounted on its own (and costly) cooler. Stacks of micro-coolers have other serious practical disadvantages, including frequent cooler failure due to cooler erosion or clogging, leakage due to o-ring failures between adjacent layers, and relatively high thermal impedance due to the edge mounted configuration.

Monolithic two-dimensional arrays of surface-emitting pump diodes are conceptually much more attractive: complete two-dimensional arrays can be processed in parallel at wafer scale, and mounted on reliable macro-channel coolers with much lower fabrication costs, dramatically smaller part counts, and lower thermal impedance. Previously demonstrated
technologies for surface-emitting lasers and arrays, such as VCSELs and grating surface emitters have not been practical for high power arrays due to issues such as high thermal/electrical impedance, extreme beam aspect ratios and instability issues. A more practical approach couples an in-plane laser to a monolithically-integrated dry-etched 45 degree turning mirror \(^5,6\); however, these mirrors tend to be optically rough, nonplanar, and inaccurately aligned. Dry-etching processes are also inherently damaging to the front facet of the semiconductor material and therefore can significantly reduce the reliability of these devices.

We have demonstrated two-dimensional surface emitting arrays utilizing 45 degree turning mirrors fabricated without dry-etching. The process makes use of a novel wet etching technique to create optically smooth mirrors with an accuracy of 0.1° or better. Figure 5 shows a schematic diagram of a single vertical emitting laser element, which employs a front facet window geometry and a 45-degree total internal reflection (TIR) turning mirror. A distributed Bragg reflector (DBR) provides feedback from the back of the laser and the light is directed through the substrate after reflection from the TIR mirror. The DBR determines the oscillation frequency, and ensures that the entire array operates at the desired pump wavelength.

![Figure 5](image)

Shown in Figure 6 are the CW L-I characteristics of a 2-D array consisting of 10 rows with 22 elements each. The array was mounted on a single macro-channel cooler for testing. The packaging for this array was designed such that each row of devices was electrically biased in series. A maximum output power of 300 W was achieved at a current of 60 A.

![Figure 6](image)
Figure 7 shows the emission spectrum at 50 A. The full width at half maximum is approximately 0.9 nm, which is much narrower than a similar Fabry-Perot array due to the frequency selective feedback from the rear DBR mirror. In addition, the oscillation frequency has much smaller temperature dependence (~0.08 nm/°C) than a Fabry-Perot. The dominant limitation on the maximum power is due to thermal roll-over, therefore further optimization in the thermal design of the package is expected to increase the maximum output power of the arrays.

Figure 7

Figure 8 is a photograph of a completely packaged array. It is noteworthy that the entire 10 row array is cooled by a single, highly reliable macro-channel cooler. A conventional edge-emitting array would require 10 individual micro-channel coolers (one for each row) and at least 20 elastomeric o-ring seals.

Figure 8

3. Advances in spatial brightness

Whether used directly, or as pumps for other lasers, high brightness high power semiconductor lasers are ideal for a wide variety of applications including the transmission of optical energy to a target and receiving a portion of it back in order to measure various physical properties of the target in a remote fashion. Diode lasers are also ideal for materials processing because of their high efficiency and compact size, light weight and ruggedness, and reduced operating cost as compared with conventional gas and solid state laser solutions. As a result, direct diode materials processing applications such as plastics welding, soldering, surface hardening, and coarse marking have become highly successful. A large number of applications including marking, cutting of non-metals and metals, and metal welding will become increasingly widespread as high brightness diodes and arrays become available.
3.1. Advances in near diffraction limited operation: 980 nm devices with 3W tapered emitters

Conventional tapered lasers typically consist of two sections, a narrow waveguide section and a tapered gain section. In the narrow waveguide section, the beam is laterally confined by a single-mode waveguide which produces a stable beam with adequate intensity. This beam is fed into the tapered gain section, where the mode is allowed to freely diffract and amplified by a tapered electrical contact. Tapered devices have been shown to reach optical output powers >1 W while maintaining near diffraction-limited beams, 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.

We have demonstrated >2W per emitter from 980 nm high power, high brightness, high yield InAlGaAs tapered lasers. Each tapered element incorporates a buried heterostructure (BH) single mode waveguide which effectively acts as a mode filter. Figure 9 shows performance data for a p-up mounted tapered 976 nm chip with a constant 200 mA in the oscillator section.

To demonstrate excellent yield of these devices, 12 emitter arrays were fabricated. The arrays were mounted junction-side-down on CS conductively cooled heatsinks for CW testing. Figure 10 is a schematic diagram of a 980 nm high brightness InAlGaAs tapered laser array. The array has 12 tapered oscillators spaced with a pitch of 900 µm. The BH single mode waveguides are ~ 1.5 µm wide and 750 µm long. The tapered gain regions are 1200 µm long and 250 µm wide at the output facet.
Figure 11 shows the CW power versus current curve for a 980 nm high power, high brightness InAlGaAs tapered laser array along with the wall-plug conversion efficiency. The array has a threshold current of 7 A and a slope efficiency of 0.86 W/A just above threshold. An output power of 35 W (~3 W per element) and a wall plug efficiency of 45% are achieved at a bias of 50 A.

![Figure 11](image1.png)

3.2. Advances in multimode brightness: 808 nm emitters with high threshold for catastrophic optical damage

The maximum optical output power of laser diodes in the 800 nm regime is 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

Quintessence Photonics Corporation has developed and optimized a proprietary high power non-absorbing mirrors (NAMs) technology called Brightlase\textsuperscript{TM}. 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. Shown in Figure 12, 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 1000 nm.

![Figure 12](image2.png)

Optical output power versus current curves of a typical 808 nm regrown NAM laser and a standard 808 nm laser are shown in Figure 13. Both devices have 50 µm wide output apertures and are from the same growth. The COD power of the non-NAM 808 nm laser is 2.3 W, which corresponds to a linear power density of 46 mW/µm. The 808 nm NAM
laser achieves an output power greater than 6 W (125 mW/µm) before failure. The longitudinal mode spectra of these 808 nm InAlGaAs lasers with regrown NAMs at a current of 2.5 A is single peaked with a spectral width of ~2 nm.

![Graph showing optical power versus current with Non-NAM and 125 mW/µm lines](image1.png)

Figure 13

Typical performance data from 100 µm stripe, 2 mm long Brightlase® nonabsorbing facet laser diodes (without internal Bragg grating) is shown in Figure 14. The device was mounted on CS-mount, with 50% efficiency and over 10 W is achieved.

![Graph showing optical power and linear power density versus current](image2.png)

Figure 14

Figure 15 shows the temperature dependence of the light-current characteristics of 100 µm stripe, 2 mm long Brightlase® lasers. Performance is shown at 20 °C, 50 °C and 70°C, and 50% wallplug efficiency at 20 °C is shown on same graph. The devices do not appear to be near thermal rollover at 7 A, and no COD is observed. Over 5 Watts is achieved at 70 °C.
The emission spectra were characterized at 3 currents and at heat sink temperatures of 20 °C, 50 °C and 70°C. As expected, Brightlase™ lasers without internal Bragg grating stabilization show emission spectra similar to standard Fabry-Perot lasers: with spectral widths are between 1 and 3 nm, with the narrower spectra at low power and wider spectra at high powers. The temperature dependence of spectrum is ~0.3 nm/ºC. The far-field distribution parallel and perpendicular to the junction were measured as a function of drive current. Parallel far fields vary with current from <5º FWHM at low current, to ~9º FWHM at high currents. Perpendicular far fields are approximately 17º FWHM and are independent of current. The main peak is nearly Gaussian and a small (~5% integrated power) subsidiary peak exists.

The reduced facet temperature provided by the NAM not only increases the COD level, but also greatly improves the reliability of the laser diode. Figure 16 shows life test data from 808 nm NAM lasers at drive currents of 2.9 A, optical power of 2.5 W, and a mount temperature of 20°C. The devices were mounted junction-down on CTE matched submounts using hard solder. No prescreening had been preformed. The devices operating at 2.9 A (50mW/µm) exhibit a degradation rate that is smaller than the noise of the measurement. Note that the 808 nm NAM chips lifetesting at a current of 2.9 A have linear power densities near the COD limit of 808 nm devices without the NAMs.

4. Advances in performance in the eye-safe wavelength regime
Diode lasers in the 1.2μm to 2μm regime are used in a variety of applications including pumping Er:YAG laser systems materials processing, and direct diode sources for 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.

Using our proprietary InGaAsP/InGaAs/InP designs, we have demonstrated reliable 1470 nm 20W operation at 20°C on
conduction cooled heat sinks with a thermal resistance of ~0.7 °C/W, and conversion efficiencies of approximately
40%, as shown in Figure 17. Lifetesting of 3 bars operating in constant current mode for over 5000 hours shows <3%
degradation as shown in Figure 18.

![Figure 17](image1)

Additionally, we have tested these devices in 50% fill factor format with 1.5 mm cavity length geometry on a water
cooled mount with thermal resistance of ~0.4 °C/W and obtained >65W at only ~160A, which is considerably more
efficient than previously reported results. See Figure 19. These designs can be scaled to considerably higher powers by
simply increasing the pumped area.

![Figure 18](image2)
Similar laser designs work well at 1532 nm, which is a very attractive wavelength for pumping eye-safe Er:YAG lasers. Figure 20 shows the performance of a 25% fill factor, 1 mm cavity length array mounted on a conduction-cooled mount. Performance is comparable to 1470 nm.

5. Conclusions

The recent advances in high brightness, high power semiconductor laser technology include 0.2 nm FWHM spectral width from single emitters with internal Bragg gratings, < 1 nm FWHM from scalable high power 2D surface emitting arrays with internal Bragg gratings, >125 mW/um 808 nm multimode performance with NAMs, >3W single mode per emitter performance from 980 nm tapered devices, and efficient reliable high power laser bar emission at eye-safe infrared wavelengths.

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