Progress of on-chip wavelength stabilization of laser diodes for seeding and pumping of high power solid state and fiber lasers

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In high power CW applications, system designers look for a reduction of the quantum defect to operate with less heat dissipation, lower risk of catastrophic damage, and enhanced conversion efficiency. The same features typically allow for reduced fiber length and nonlinearities in high peak power fiber amplifiers, enabling higher energy extraction and higher performance. However, such preferred wavelengths often have narrow absorption bandwidths and require pumping with narrow emission linewidth as well as accurate center wavelength, such as 1532nm for Er:YAG [1]. Quasi-CW operation of pump diodes would also greatly benefit from a reduced wavelength temperature coefficient, limiting thermal effects linked to steep variation in driving current and maintaining a narrow bandwidth required for efficient pumping. Finally, several defense applications require pump diodes to maintain accurate center wavelength in operation despite temperature variations as high as 80ºC. It is therefore critical to improve the stability and the spectral narrowing of high-power laser diodes so that they can simultaneously deliver the efficiency associated with diode pumping and temperature-insensitivity provided by lamp pumping.

Recently, these challenges have been overcome for high power lasers over a broad range of wavelengths from 792 to 1550nm. These MOCVD-grown GaAs-based and InP-based lasers (Brightlock™) include internal gratings that narrow the spectral linewidth down to <0.2nm, reduce wavelength-temperature sensitivity to <0.1nm/ºC, and ensure that the device operates at the required wavelength. These devices are fabricated using a wafer-based process, with the gratings defined after a first epitaxial growth by optical lithography into a photoresist layer, followed by etching, then finalized during a re-growth process.

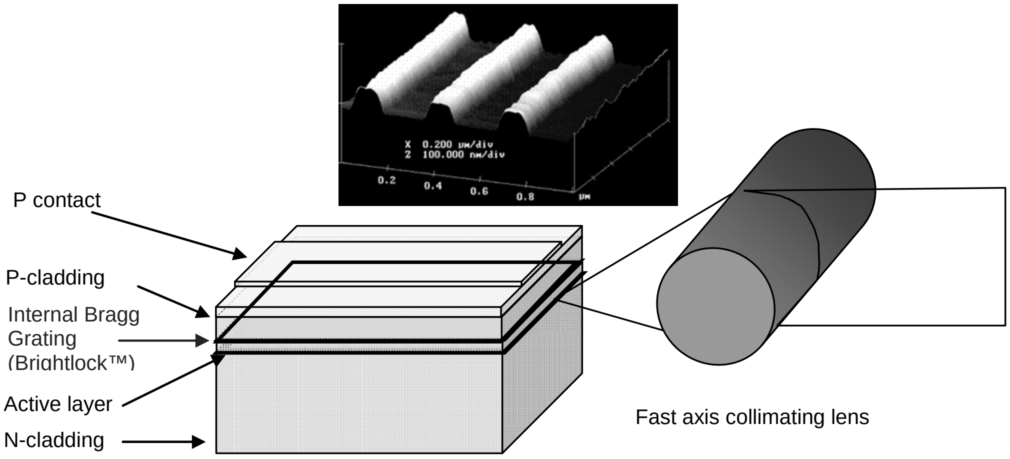

Figure 1. Schematic describing the internal Bragg grating fabricated during MOCVD growth to provide narrow spectrum and reduced sensitivity to temperature. The technique is applied to both GaAs and InP based high power semiconductor laser diodes.

Characteristics of on-chip wavelength-stabilized high power laser diodes at 7xxnm-8xxnm

Recent investigations, based on extensive analysis of gratings parameters and waveguide geometry, have led to a dramatic improvement in conversion efficiency of wavelength-stabilized bars at short wavelengths with efficiency reaching 50% from a 45W CW conduction-cooled bar as shown in figure 2. The narrow spectrum and high efficiency from the high power bar makes it an ideal pump candidate for diode-pumped Alkali laser (DPAL) [2]. A major advantage versus wavelength stabilization performed by a Volume Bragg Grating stems from the fact that power scaling and low cost of manufacturing can be maintained even at power levels consistent with multiple bars configurations, such as vertical stacks, because the monolithic on-chip wavelength stabilization scheme eliminates the need for complex alignment of expensive optics while improving yield and reliability.

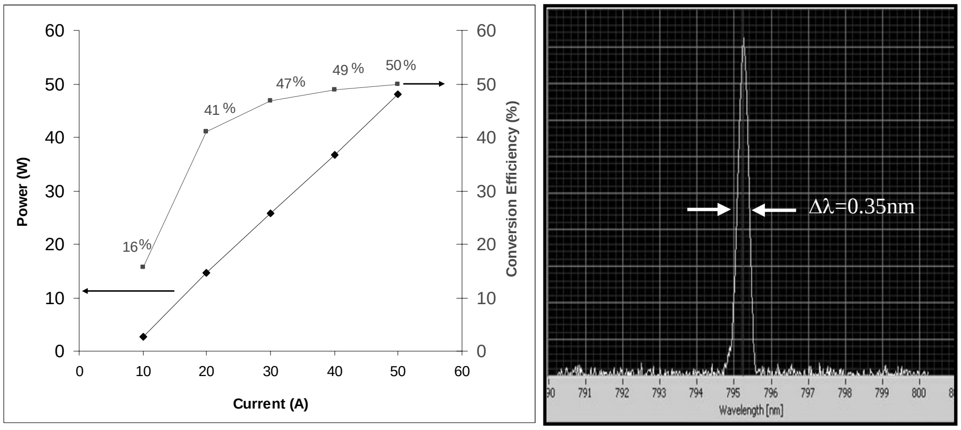

Figure 2: Power versus current for a 19 emitter 795nm Brightlock CS-bar conduction-cooled at 20C. Conversion efficiency reaches 50% at 50A. Spectrum FWHM is 0.35nm.

On-chip Internal Bragg gratings also enable high temperature operation of pump diodes with center wavelength locked and tuning at only 0.07nm/°C with demonstrated locking to 70°C. The reduced wavelength temperature coefficient enables pumping efficiently without TEC cooling by locking the pump emission wavelength inside the crystal absorption band. Green laser efficiency is improved by up to 80%.

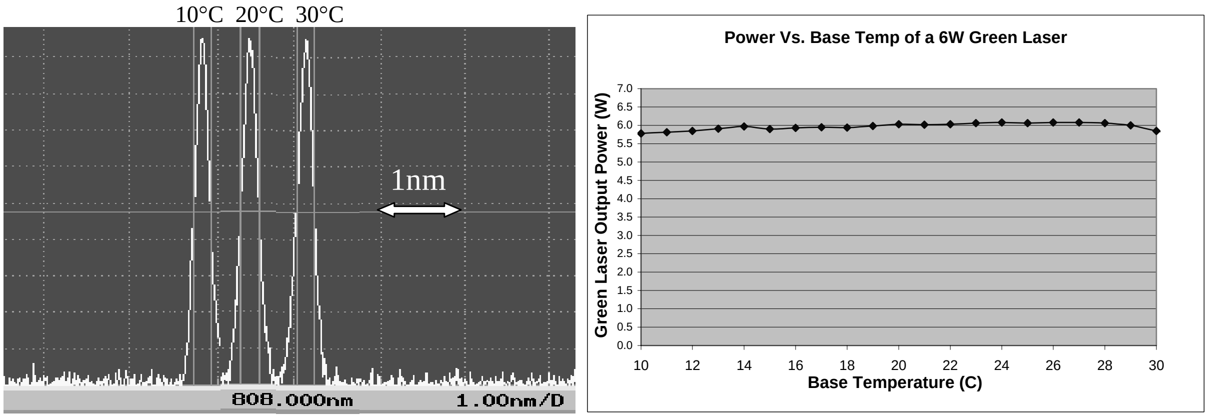

Figure 3. Variation of center wavelength versus temperature for a 1cm Brightlock™ CS-bar at 808nm (left). The reduced sensitivity to temperature of the pump diode spectral features maintains its emission bandwidth within the absorption bandwidth of a Nd:YVO4 crystal in a frequency-doubled DPSS configuration, producing 6W of constant CW power from 10C to 30C (right).

Characteristics of on-chip wavelength-stabilized high power laser diodes at 14xxnm-15xxnm

InP based pump diodes are critical for a number for high power laser diode efforts. Resonant pumping of Er:Yag at 1532nm is a well known method to achieve high efficiency and reduced heat dissipation for “eyesafe” directed energy systems [1]. QPC has developed waveguide designs that reduce the far-field divergence of long wavelength bars and enhance their spectral purity for improved spatial and spectral brightness.

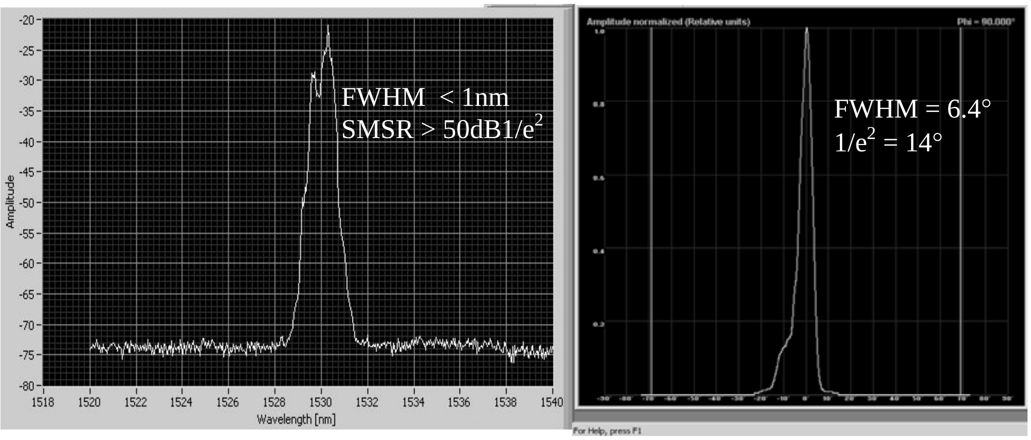

Figure 4. Spectrum on logarithmic scale (left) and slow axis far-field divergence (right) of a typical high power 20W CW conduction-cooled 1532nm Brightlock bar.

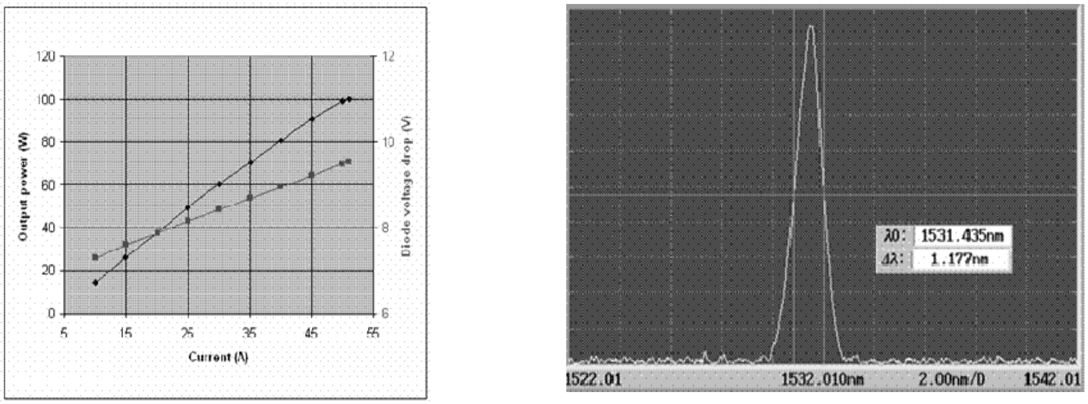

Figure 5. LIV of a 100W, 1532 nm fiber-coupled diode laser module with internal grating stabilization

The wafer-scale approach to wavelength stabilization also enables vertical stacking of dozens of bars and power scaling to kW level without compromising reliability or spectral brightness. In addition, these bars operate well in QCW operation, with steady-state conditions reached after only a short 50ms settling time [3].

High spectral and spatial brightness from MOPA devices

QPC has recently demonstrated record power from MOPA devices at various wavelengths, with over 10W CW at 1064nm with a single spatial and longitudinal mode, and up to 700mW CW at 1550nm from a single mode fiber, with a linewidth measured at 500 kHz by Yariv's group [4], making it an ideal source for direct diode LIDAR or seed for narrow linewidth fiber laser. When used at pumping wavelength such as 1532nm, these devices enable scaling of high spatial and spectral brightness resonant pumping to new levels, especially for eyesafe fiber laser pumping.

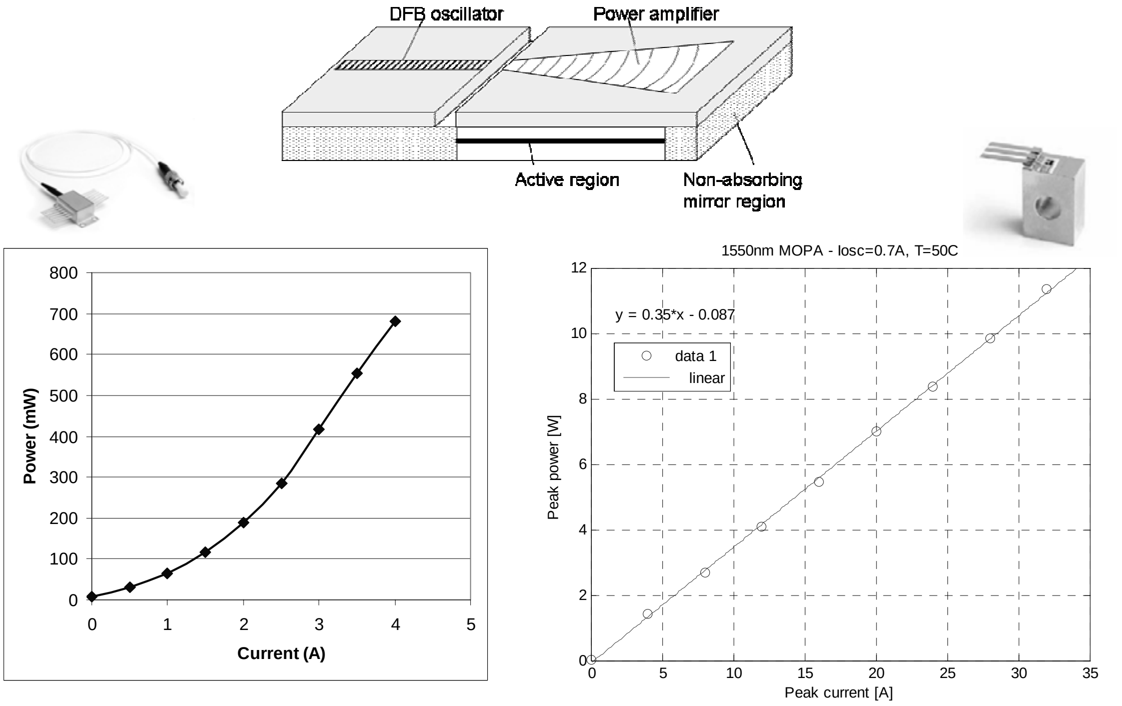

Figure 6. MOPA device at 1550nm produces 700mW CW out of a single mode fiber with a linewidth of 500 kHz (left). Peak power exceeding 10W with 50ns pulse width, 10kHz at 50C is obtained from a C-mounted device.

Given the high spatial beam quality and watt level power achieved from individual MOPA device, it becomes possible to scale up power of fiber-coupled devices using "bar" and "stack" configurations to >150W from a 100µm, 0.15NA fiber. Indeed, the beam product of a 100µm 0.15NA fiber is 30mm•mrad; and the beam product of a 1550nm single emitter with diffraction limited beam quality is about 2. In theory, one can therefore couple 225 such single emitters arranged in a 15 x 15 matrix into the fiber. However, one needs to consider heat dissipation, bar bonding issues and lens array dimensions, which practically limit the number of emitters per bar to 8 emitters. After FAC lens collimation, each bar is expected to output a ~0.9mm beam with <3mrad remaining divergence. The beams from 2 identical stacks can then be spatially interleaved to output 120W optical power from 80 emitters. Power can then be doubled through polarization combining without sacrificing spatial beam quality. Assuming a reasonable 70% overall optical coupling efficiency, 168W CW power can therefore be obtained from a 100um/0.15NA fiber. Such a brightness level will enable resonant pumping of eyesafe fiber lasers for next generation direct energy systems.

References

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