High-spectral brightness pump sources for diode-pumped solid state lasers

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ABSTRACT

The development of on-chip grating stabilized semiconductor lasers for diode pumped solid state lasers is discussed. The diode lasers, specifically at wavelengths of 808nm, 976nm, and 1532nm are stabilized via internal gratings to yield a typical center wavelength tolerance of ± 1nm, FWHM of < 1-2nm, and a temperature tuning coefficient of < 0.09 nm/°C. We also report on the CW and QCW operation of conduction cooled bars, stacks, and fiber coupled modules. Simulations show that on-chip stabilized pump sources yield performance improvements over standard pumping schemes. A comparison in laser performance is shown for typical DPSS configuration.

Keywords: High power laser diodes, Wavelength stabilization, Fiber lasers, Solid state laser, Athermal pumping, Diode-pumped, High brightness

1. INTRODUCTION

Benefits of pump wavelength stabilization for diode pumped solid state pumping include dramatic improvements in laser system compactness, efficiency, brightness, and beam quality while simultaneously reducing thermal management cost and complexity in the system. QPC has recently introduced high power diode lasers with on-chip gratings which narrow the linewidth and stabilize the wavelength, thereby offering "athermal" performance similar to lamp pumping while maintaining the much higher efficiency of diode pumping at common pump wavelengths and in the eye-safe regime. Recent developments have enabled QPC to reach efficiency of 50% from a 19 emitter array at short wavelengths, decreasing significantly the power penalty typically associated with wavelength stabilization. For high energy and low noise fiber laser pumping, over 300W is demonstrated from a fiber-coupled pump block with less than 0.5 nm spectral width. Finally, a record 500W CW was obtained from a two dimensional array of wavelength-stabilized surface emitters.

2. MOTIVATION FOR ON-CHIP GRATING TECHNOLOGY (BRIGHTLOCK™)

Systems based on traditional laser diodes cannot deliver the temperature independent performance of lamp-pumped designs. Instead precise thermal management and temperature control of the diode is needed to precisely tune the emission wavelength, and even with this control insufficiently narrow linewidths are produced, reducing overall system efficiency and unwanted heat dissipation. In addition, as the number of pumps increase with the laser's average power, the wide distribution of center wavelengths between pump diodes prevent a simple, unique cooling system since some diodes need to be cooled while others need to be heated to reach the desired absorption wavelength.. Finally, several emerging markets including medical and defense applications as well as portable laser displays prefer passively cooled solutions whenever possible to reduce cost, ambient noise and overall footprint.

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High-Power Diode Laser Technology and Applications VII, edited by Mark S. Zediker,
Proc. of SPIE Vol. 7198, 71981R · © 2009 SPIE · CCC code: 0277-786X/09/$18 · doi: 10.1117/12.805096

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-stability provided by lamp pumping. If these objectives are met at a well-defined wavelength, then laser system designers can improve the system's compactness, efficiency, power, and beam quality while reducing its thermal management cost.

Various methods have already been used to improve the spectral brightness, stability and accuracy of laser diodes. These approaches include various external techniques using either volume Bragg gratings, external lenses and bulk gratings. Emission based on external volume Bragg grating stabilization typically offer very narrow linewidth (<0.1nm) and very low wavelength temperature coefficient, typically on the order of 0.01 nm/C.

However, approaches based on external components require sensitive and high-precision alignment, costly additional lasers and/or optics and specially designed coatings which can become a source for reliability concern. Also, because the diode gain continues to shift at a rate of about 0.3 nm/C in external cavity configurations, the operation of the laser diode is restricted to a narrow current range to maintain wavelength locking over the entire laser bandwidth [1]. Finally, although the great wavelength stability versus ambient temperature (~0.01nm/C) and very narrow bandwidth (~0.1 nm) of a diode locked with external component is attractive for some spectroscopy and low noise applications, these features are not always desirable for standard pumping applications if the emission is too narrow or fine-tuning is needed.

	Spectral brightness	Athermal operation	Pump efficiency	System Efficiency	Locking range vs current, T	Tunability	Wafer-scale Manufacturing
Flashlamp pumping		✓✓✓✓	✓	✓			
Traditional diode pumping	✓	✓	✓✓✓✓	✓✓		✓✓✓✓	✓✓✓✓
VBG-stabilized diode pumping	✓✓✓✓	✓✓✓✓	✓✓✓	✓✓✓	✓✓	✓	✓
Brightlock diode pumping	✓✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓	✓✓✓✓

Table 1: Feature comparison between various solid state laser pumping methods.

3. FEATURES OF ON-CHIP WAVELENGTH STABILIZATION

Recently, QPC has overcome these challenges and demonstrated a range of high-power lasers operating at 795, 808, 976, 1064, 1470, 1532 and 1550 nm, which are fabricated at our headquarters in Sylmar, CA.

Traditional diodes	**BrightLock™ Internal Gratings**
• Center wavelength : +-3nm	• Center wavelength : +-0.5nm
• Sensitivity to temp: 0.3nm/C	• Sensitivity to temp: 0.07nm/C
• Spectral width: 2-4nm FWHM	• Spectral width: <0.5nm FWHM

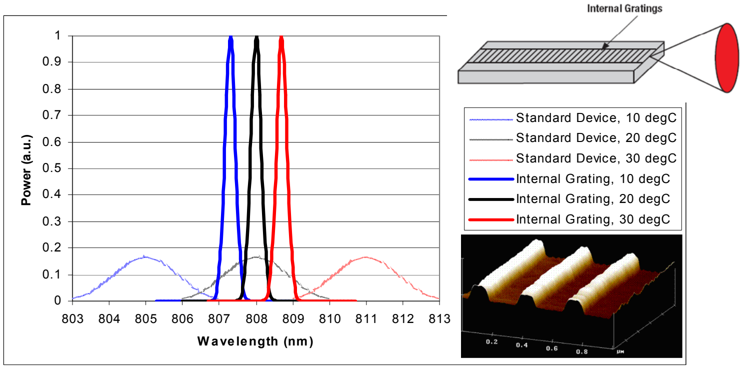


Figure 1: Comparison of spectral features between standard and Brightlock™ laser diodes.

Labeled “BrightLock™” for their unique combination of spectral brightness and wavelength stabilization properties, these MOCVD grown InP-based and GaAs-based lasers feature internal gratings that narrow the spectral linewidth down to less than 0.5 nm, reduce wavelength-temperature sensitivity by 400%, and ensure that the device operates at the required wavelength as shown in fig.1. These devices are fabricated in a similar way to conventional laser diodes, with the gratings defined by optical lithography into a photoresist, followed by etching, or formed during a growth and re-growth process. High spectral brightness from on-chip wavelength stabilization can also be combined with QPC’s Brightlase® technology for unmatched brightness performance from laser diodes.

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.

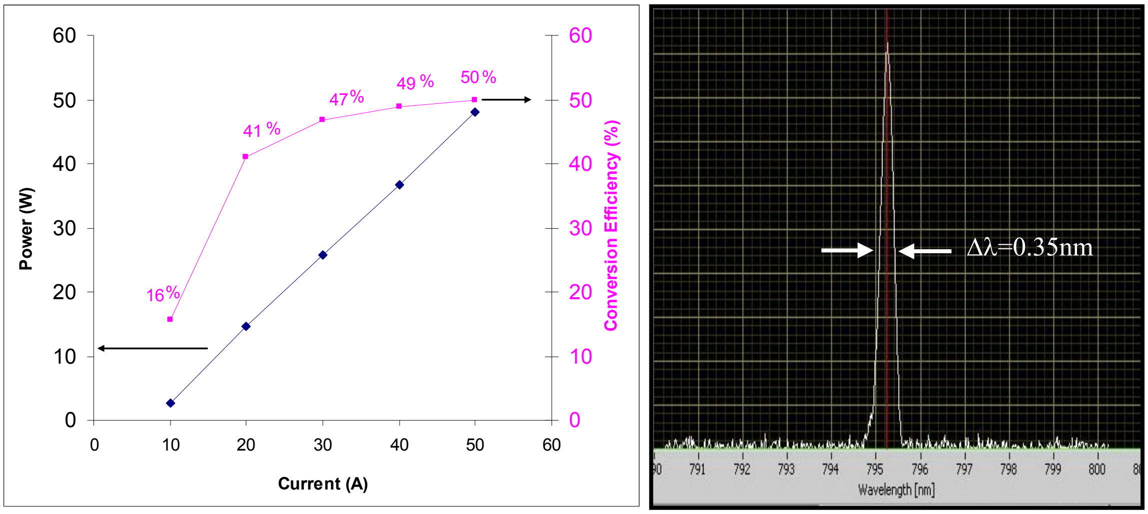
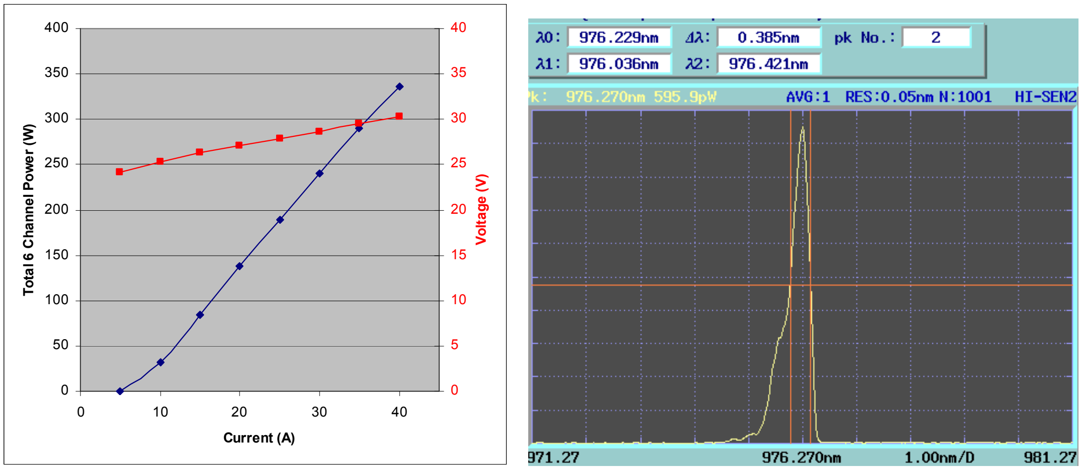


Figure 2: Power versus current for a 19 emitter 795nm Brightlock CS-bar conduction-cooled at 20C. Conversion efficiency reaches 50% at 50A. Spectrum FWHM is 0.35nm.

4. HIGH SPECTRAL BRIGHTNESS PUMPS FOR HIGH PEAK POWER FIBER LASERS

In high peak power nanosecond and marking fiber lasers based on Yb or Er:Yb based materials, high absorption per unit length is preferred at 976 nm to minimize nonlinearities and improve conversion efficiency [2]. However, absorption at 976 nm is relatively narrow and requires accurate center wavelength, narrow bandwidth and stability versus temperature from pump diodes. Several very promising materials for high power thin disk lasers such as Yb:Lu2O3 or Alkali-vapor lasers also rely on such pump diode performance to unleash their potential. Also, Leading architectures being proposed for high power directed-energy laser weapons envision the coherent combination of multiple beams from multiple lower-power fiber lasers or fiber amplifiers into a single high power beam. Successful beam combining will require short fiber amplifiers with very low phase noise. Such low noise can be achieved by pumping with a stable, narrow bandwidth pump to

An example of such a module is shown in fig. 2, demonstrating 330W of optical power with a bandwidth of less than 0.5 nm. The combined output offers a dramatic reduction of the wavelength temperature coefficient from 0.3 nm/C to 0.074nm/C. Similarly, the center wavelength accuracy as a function of applied current is measured at 0.089nm/A, showing great promise for QCW operation of these devices.

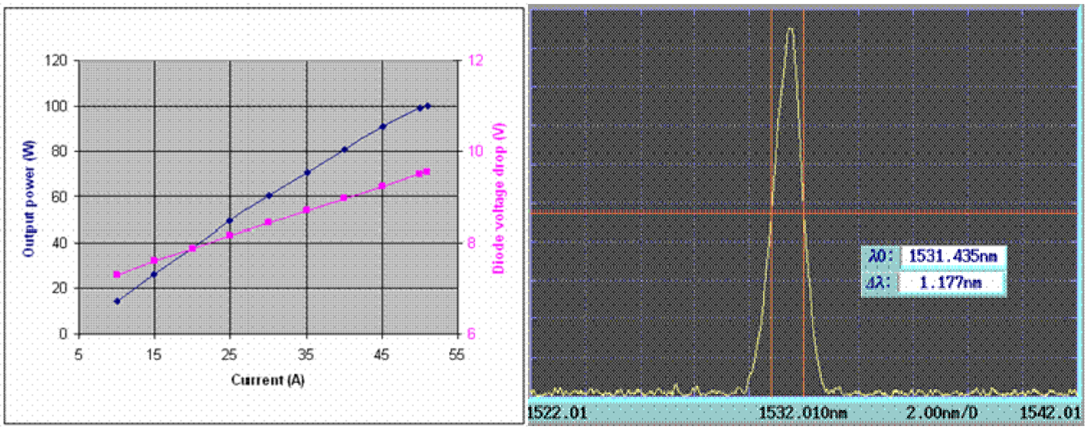


λ0: 976.229nm Δλ: 0.385nm pk No.: 2
λ1: 976.036nm λ2: 976.421nm
k: 976.270nm 595.9pW AVG:1 RES:0.05nm N:1001 HI-SEN2

Figure 3: On-chip grating stabilization of laser diodes enables high power, narrow bandwidth and reduced sensitivity to temperature. A 6 channel module is shown here producing 330W at 976nm with <0.5nm bandwidth for fiber laser pumping

5. IMPROVING SYSTEM EFFICIENCY IN HIGH ENERGY LASER SYSTEMS

In high power CW applications, system designers look for a reduction of the quantum defect, defined as the difference in wavelength between laser emission and absorption wavelength. Lasers operating with a reduced quantum defect operate with less heat dissipation, lower risk of catastrophic damage, and enhanced conversion efficiency. However, it is often the case that such preferred wavelengths have narrow absorption bandwidths and also require pump lasers that have good center wavelength accuracy, narrow bandwidth and are relatively insensitive to temperature shifts. A good example of such paradigm is high energy Er:Yag solid state laser pumping where on-resonance pumping at 1532 nm enables higher efficiency and easier thermal management by operating close to the 1645nm emission linewidth of the laser.



λ0: 1531.435nm
Δλ: 1.177nm

Figure 4: Wavelength stabilization at 1532nm yields a 10x spectral brightness enhancement over un-stabilized diodes. Data is shown for a 100W, 400µm fiber-coupled module with spectral bandwidth of less than 1.2nm.

Quasi-CW operation is also becoming more popular among high power laser system designers for low repetition rate operation. This mode allows minimizing amplified spontaneous emission and extracting more peak power from laser diodes that would be otherwise thermally limited. However, as the current is increased at the rising edge of the electrical pulse, the spectral bandwidth of the pump diode increases due to a significant rise of the laser junction temperature. For pulses beyond several microsecond, this feature can drive the emission bandwidth of the pump diode outside of the absorption bandwidth of the gain medium, reducing efficiency of the overall system.

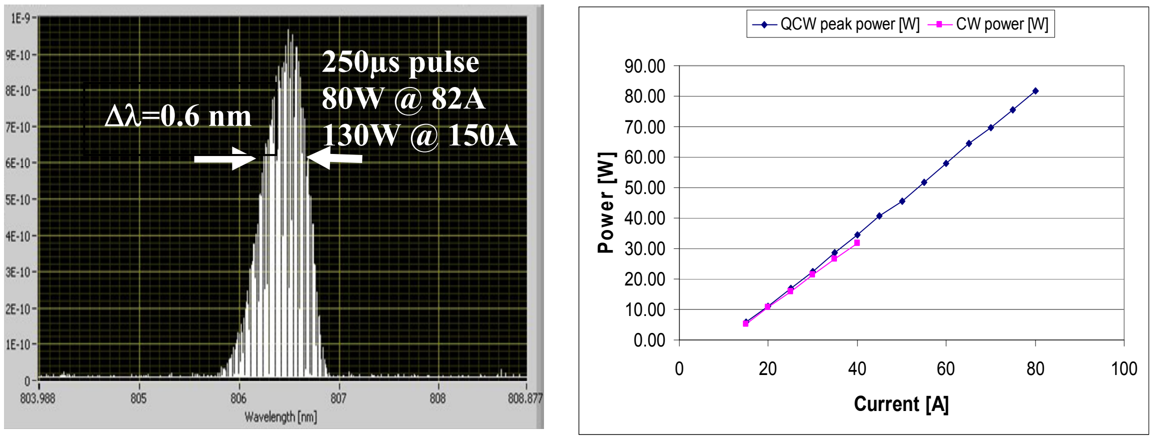


Figure 5: Spectrum of a Brightlock 19 emitter array at 808nm during QCW operation at 82A, 250µs/25 Hz.

Even higher spectral brightness can be obtained with vertical stacks of wavelength-stabilized diodes. Up to 700W has been demonstrated with a bandwidth of less than 2nm and QPC is working on a 10kW module for industrial application to be delivered by mid-2009. The major advantage of Brightlock on-chip wavelength stabilization for this platform is that it enables standard lensing of the stacks, which is a very difficult and expensive task with a Volume Bragg Grating approach. Recently, transient effects of high power stacks with internal gratings were studied and showed that steady-state conditions were reached after only a short 50ms settling time [3].

6. MONOLITHIC 2D BRIGHTLOCK PUMP ARRAY

On-chip wavelength stabilization technology leverages wafer-scale technology to reduce cost and eliminate costly components and complex alignment required with VBG technology. For very high power, dramatic further cost reduction can be obtained by eliminating individual lensing of arrays and complex cooling.

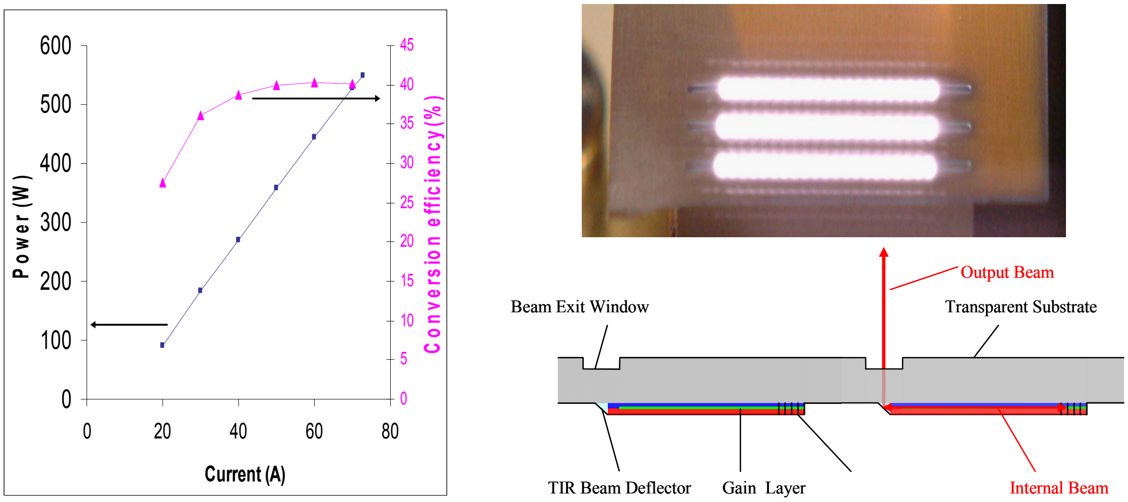


Figure 6: >500W CW obtained from a two dimensional array of Brightlock surface emitter diodes. Efficiency reaches 40%.

Through funding from US Army and US Navy, QPC has spent several years developing technologies based on a monolithic array of Brightlock™ surface emitters. A two-dimensional array of Brightlock surface emitters can be collimated using a single lens array and cooled through single cooler without de-ionized water. Recent results have demonstrated power over 500W CW from a two dimensional array of twelve bars as shown in figure 6.

7. PASSIVELY COOLED PUMPS FOR LOW COST DPSS

Finally, as well known traditional diode-pumped solid state lasers are moving into applications that are required to operate in severe environmental conditions for defense or portable consumer electronics applications, pump diodes are required to maintain accurate center wavelength in operation despite temperature variations as high as 80º C.

Internal gratings also enable high temperature operation of pump diodes with center wavelength locked and tuning at only 0.07nm/ºC up to at least 60ºC, as shown in fig.3. 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%.

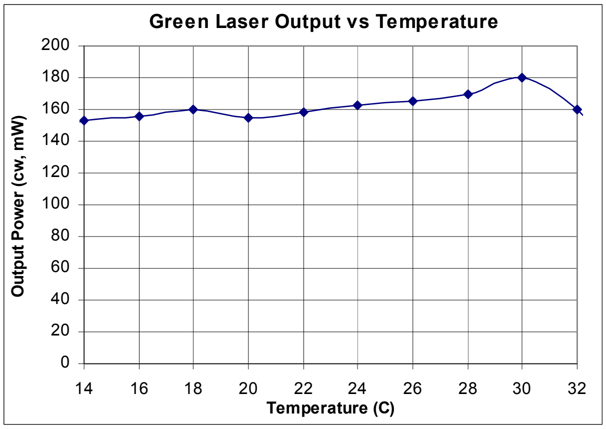


Figure 7*: Power versus current measured at 532nm from a Nd:YVO4 DPSS 150mW laser pumped with a 808nm Brightlock® chip.*

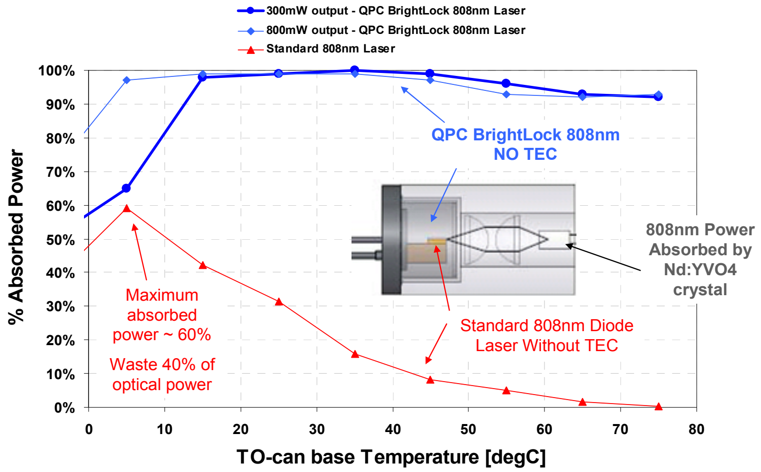


Figure 8: Modeling of 808nm power absorption by Nd:YVO4 crystal for Brightlock versus traditional 808nm laser diode pump.

8. ULTIMATE SPECTRAL BRIGHTNESS

QPC, with seed funding provided by the US Navy, is developing a new generation of pump modules that will enable high performance fiber lasers/amplifiers suitable for efficient beam combining. These modules, which are based on unique MOPA diode architectures, provide unprecedented pump spatial brightness and are suitable for fiber laser pumping. Moreover, they incorporate Brightlock internal diffraction-grating wavelength stabilization to maintain a narrow emission line centered on the absorption peak. Both of these factors enable short length, reduced nonlinearity fiber lasers and amplifiers that are suitable for beam combination.

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]. When used at pumping wavelength such as 1532nm or 976nm, these devices will enable scaling of high spatial and spectral brightness resonant pumping to new levels.

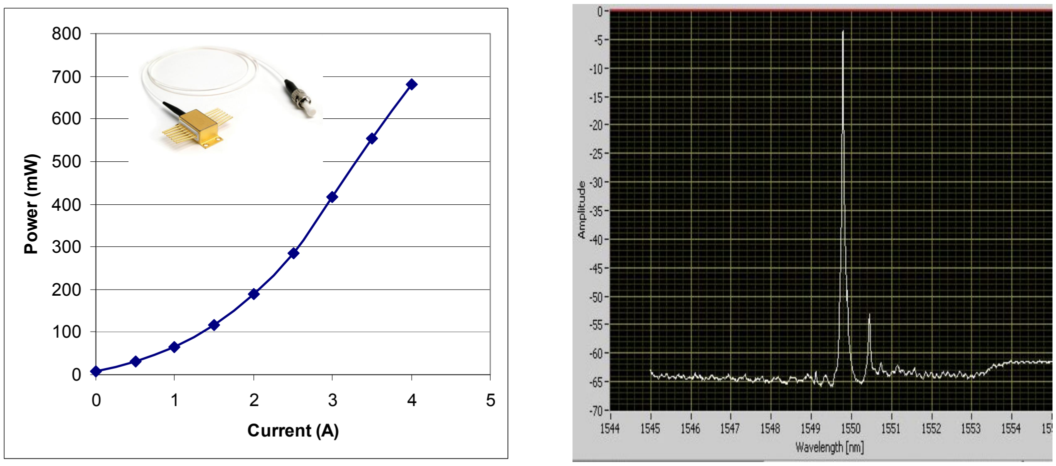


Figure 9: MOPA device at 1550nm produces 700mW CW out of a single mode fiber with a linewidth of 500 kHz. Such devices will enable further spatial and spectral scaling of high energy laser pumping at 1532nm and 976nm.

9. CONCLUSION

On-chip wavelength stabilization (Brightlock™) enables "athermal" solid state pumping and eliminates the need for thermoelectric cooling in low power applications. Conversion efficiency of 50% from a full 19 emitter array has been demonstrated at 795nm and over 300W from a fiber-coupled module at 976nm within a spectrum full width half maximum of less than 0.5nm. Development of 2D Brightlock surface emitters already shows great promise with 500W CW already demonstrated with 40% conversion efficiency. Finally, MOPA devices offer the ultimate brightness at 1532nm and 976nm for scaling of high energy laser pumping with devices producing up to 700mW CW and linewidth of 500 kHz out of a single mode fiber.

ACKNOWLEDGEMENTS

Part of this work was supported by the Naval Air Warfare Center Weapons Division under Contract Number N68936-040C-0028, DARPA ADHELs program, and by the US Army CECOM under contract DAAB07-03-C-L415.

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