Narrow-line, tunable, high-power, diode laser pump for DPAL applications

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ABSTRACT

We report on a high-power diode laser pump source for diode-pumped alkali lasers (DPAL), specifically rubidium alkali vapor lasers at 780nm, delivering up to 100W/bar with FWHM spectral line width of 0.06nm (~30GHz). This pump is based on a micro-channel water-cooled stack with collimation in both-axes. Wavelength-locking of the output spectrum allows absorption in one of the very narrow resonance lines of the atomic rubidium alkali vapor. To achieve these results, research was conducted to deliver the highest performance on all key components of the product from the diode laser bar which produces the optical power at 780nm to the external Bragg gratings which narrow the spectrum line width. We highlight the advancements in the epitaxy, device design, beam collimation, grating selection, alignment, tunability and thermal control that enable realization of this novel pump-source for DPALs. Design trade-offs will be presented.

Keywords: diode lasers, Bragg gratings, diode laser tunable stacks, narrow line width

1. INTRODUCTION

Over the past decade, diode pumped alkali lasers (DPAL) have emerged as a new class of gas lasers which have the capability to deliver multi-kW, CW mode, diffraction-limited optical power but are currently limited by the lack of availability of reliable, high-power, high-efficiency, narrow line-width diode laser pump sources. The virtues of DPAL are widely reported in the literature [2,3,4] and in this paper we focus on the pump source which moves us closer to realization of DPAL’s full potential. The key differentiating attribute of the diode pump source which makes it unique for DPAL application is the extremely narrow bandwidth at high CW output power. For example, when pumping rubidium alkali vapor at 780nm, the desired bandwidth (FWHM) of the output spectrum at full CW power must be less than 100GHz (or 0.1nm). This narrow-bandwidth specification coupled with the required high CW output powers are the critical design challenges, along with the tunability for the DPAL diode pump source. We report on a 780nm, CW, line-narrowed, tunable, pump source comprised of a micro-channel cooled, diode laser stack with wavelength-locking of the output spectrum by external Bragg gratings.

Diode laser stacks, which are widely used in the industry, consist of a high-power diode laser bar bonded to a heat sink which can be either vertically or horizontally stacked in an array. The average power level of the diode bar determines the type of heat sink to be used in the stacked array e.g. for lower average power (<10W/bar) a conductively cooled heat sink is sufficient but for higher powers, heat removal is achieved by mounting the laser bar on an actively cooled heat sink (micro-channel cooler) which has cooling water channels running directly under the diode. The micro-channels are a 3-D layered copper structure [1] to minimize the thermal resistance and therefore maximize power output by delaying the onset of thermal rollover. Industrial applications often demand high power density (W/cm²) and the most effective way to achieve that is to maximize the power per bar and reduce the overall stack emission pitch by compressing the stacked arrays as close together as possible. To maximize the power per bar, all individual steps which contribute to the final product performance must be carefully engineered starting at the diode device design, and continuing through epitaxy design, epitaxy growth, wafer processing, facet coating, soldering, heat sink design, and final packaging. To achieve a narrow output spectrum as mentioned above, Bragg gratings were developed with the optimum diffraction efficiency and size to realize the spectral bandwidth (FWHM) and wavelength tuning range.
We present electro-optical (E-O) and life test data of a typical 780nm diode laser bar operating at 100W, CW, output power, bonded on micro-channel cooler as well as a wavelength-locked single-bar and multi-bar stack. We also report on the wavelength tunability via thermal control of the Bragg grating.

2. LASER BAR PERFORMANCE FOR DPAL

This section presents data of individual diode laser bars for DPAL applications. As shown in Fig. 1, each diode bar is mounted with indium solder to a micro-channel cooler heat sink [5].

![Diode bar mounted on a micro-channel cooler](image)

Figure 1. Diode bar mounted on a micro-channel cooler with dimensions W x L x H of 11mm x 27mm x 1.8mm.

2.1 Laser bars at 780 nm for Rb laser pumping

Diode laser bars, with a tensile-strained quantum-wells (TM polarized), comprised of 19 emitters, with 90µm emitter width on 500µm pitch (18% fill-factor), 3mm resonator length, and standard AR coating were mounted on micro-channel cooled heat sinks then characterized for basic electro-optical (E-O) properties. Typical results are shown in Figures 2 to 7.

![Power-Current-Efficiency curve](image)

Figure 2: Power-Current-Efficiency (P-I-E) curve of an 18%FF bar, 3mm cavity length, indium solder-mounted to a micro-channel cooled heatsink.
Figure 3: Typical spectrum measured at 104W, CW, 20°C water-inlet temperature

Figure 4: Spectral shift as a function of output power: Note: SP is short pulse mode with negligible waste heat.
Figure 5: Spectral shift as a function of operating current

Figure 6: Spectral shift as a function of output power

Figure 7: Far-field divergence (95% power content) as function of output power
2.2 Life test plots

A set of two bars was also life tested at constant current at initial power levels of 80W, 90W and 100W. Life test plots are shown in Figures 8 to 10 and results summarized in Table 1.

Figure 8: Life test plot of two diodes started at 80W output power, CW mode, 20°C

Figure 9: Life test plot of two diodes started at 90W output power, CW mode, 20°C

Figure 10: Life test plot of two diodes started at 100W output power, CW mode, 20°C
Figures 8-10 chart the life tests of a set of two diode bars operating at each of three fixed operating currents and at an inlet water temperature of 20°C. All tests were terminated at 590 hours. A summary of the life test results is tabulated in Table 1. At 80W power level, both diodes degraded by an average of ~12% within 590 hours (measured power numbers for each set is shown in Table 1.) The end-of-life power is depicted by the red-line on each graph and is defined as 20% drop in power from time = 0 hours. The projected end-of-life hours at each operating condition is shown in second to last column in Table 1. Note that the sample size is too small to extract a complete reliability specification and therefore the end-of-life hours (defined as 80% of initial power) were calculated by a linear, constant degradation rate with extrapolation to 80% of initial power.

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<th>$P_{\text{test}}$ (W)</th>
<th>$I_{\text{test}}$ (A)</th>
<th>$P_{\text{opt}}$ (W) @ 0h</th>
<th>$P_{\text{opt}}$ (W) @ 590h</th>
<th>$t_{\text{EOL}}$ (h)</th>
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Table 1: Summary of Life Test Results

3. 780NM, SINGLE-BAR, WAVELENGTH-LOCKED, STACK PERFORMANCE

In this section we present results of a wavelength-locked, single-bar, water-cooled stack comprised of the diode-laser bar described in section 2. This single-bar stack was based on DILAS’ commercially available package. For wavelength-locking experiments, we used a low AR coated front-facet bar and micro-optics to collimate both axes in order to maximize feedback of diffracted light from the Bragg grating (also referred to as volume holographic grating, or VHG) into the laser bar cavity. A 5mm thick, 13mm long and 1.5mm clear aperture VHG, supplied by Ondax Inc., was used in this experiment. Figure 11 shows a schematic of the layout. Fast-axis beam and slow-axis beam divergence were measured at 3mrad (90% power content) and 21mrad (90% power content) respectively (see Figure 13).

For each Bragg grating, there is direct relationship between angular divergence of the input beam and the fraction of diffracted light reflecting back into the laser cavity. Figure 12 shows the simulated theoretical spectral and angular response of a 5mm long, 10% VHG based on coupled wave equations for the gratings [6]. Figure 12 (inset picture on top left), shows that the diffraction efficiency is ~10% within a +/-5mrad angle of incidence, i.e. 10% of the diffracted light is reflected back into the laser cavity, but drops rapidly at higher incidence angles. For example at an +/-9mrad angle of
incidence, the effective diffraction efficiency is ~2.5%. Hence, it is clear that to maximize feedback of the VHG’s center wavelength back into the laser bar cavity, the beam’s divergence must fall within the +/-5mrad acceptance angle of incidence. For the bars used here, the fast-axis is well within this acceptance angle of incidence for complete feedback, however the slow-axis has a measured divergence of 21mrad (or +/-10.5mrad). Since only the fraction of incident beam energy which is inside a roughly +/-5mrad angular envelope (fast-axis and slow-axis combined) is seen by the diode as VHG feedback, the VHG has an effective diffraction efficiency of only ~1% at 780.0nm. While this portion of energy can be theoretically estimated by modeling the beam as Gaussian for the fast-axis and super-Gaussian for the slow-axis, then calculating the power content within +/-5mrad for the combined envelope, for practical purposes, we estimate <30% of the energy within the incident beam is effectively reflected back into the laser cavity. Hence a 10% diffraction efficiency grating is effectively a 3% diffraction efficiency grating, without accounting for further losses due to misalignment of the grating with respect to the bar front facet, losses due to bar smile, or optical losses within the grating itself.

Figure 12: Theoretical model of angular and spectral response of 10% VHG (courtesy of Ondax Inc.).

3.1 E-O characteristics of the single-bar stack

Figure 13 shows the output power as a function of drive current for a free-running stack (no VHG) and the same stack VHG-locked with gratings of diffraction efficiencies of 6.3%, 9.4% and 12.3%. These curves are almost identical for all scenarios, indicating that a free-running bar can be VHG-locked with negligible power penalty using any VHG in the range of 6.3% to 12.3% diffraction efficiency. It is important to note that the threshold current does increase compared to a standard AR coated diode bar (shown in figure 2) from ~10A to ~13A which is consistent with an AR coated bar. Further investigation is warranted to determine why the effective diffraction efficiencies of all gratings are very similar and why we do not observe any measurable change in threshold current and slope efficiency of the VHG-locked bar.
Figure 13: Power vs. current curve of single-bar stack with and without wavelength-locking.

Figure 14: Left graph shows a plot of fast-axis divergence (3.1mrad, full width, 90% power content). Right graph shows a plot of slow-axis divergence (21mrad, full width, 90% power content)

3.2 Spectrum of a free-running single-bar stack

Figure 15 show the output spectrum of free-running single-bar stack with FWHM of 2.5nm, center wavelength of 779.5nm, temperature of 28°C, operating current of 80A. Figure 16 captures the spectrum of a VHG-locked bar at full power with a 6.3% diffraction efficiency grating (note different scales for the x-axis).
Figure 15: Output spectrum of free-running single-bar stack (FWHM is 2.5 nm).

Figure 16: Screen image of output spectrum from a wavelength-locked single-bar stack measured by a Yokogawa OSA model AQ6370C, with center wavelength (in vacuum) of 780.3570 nm and 3dB bandwidth of 0.0536 nm at 100 W, CW, output power.

3.3 Spectral response of single-bar stack

Figure 17 shows the locked center wavelength shift as a function of optical power at the rate of 3 pm/W.
For back reflection the Bragg wavelength $\lambda_B$ is a function of refractive index $n$ and grating spacing $\Lambda$:

$$\lambda_B = \frac{2}{n} \Lambda$$

The grating layers are recorded throughout the volume of the glass. Therefore the grating spacing follows the linear thermal expansion of the bulk material. In addition the refractive index varies with temperature $T$. Both effects contribute to the change of Bragg wavelength $\Delta \lambda_B$ as a function of temperature change $\Delta T$:

$$\Delta \lambda_B = \lambda_B \left( \alpha + \frac{1}{n} \frac{\partial n}{\partial T} \right) \Delta T$$

Here $\alpha$ is the linear thermal expansion coefficient and $\alpha_{\text{eff}}$ the effective wavelength tuning coefficient. This linear approximation holds well for temperatures between 0 and 100 $^\circ$C. The effective wavelength tuning coefficient is $\alpha_{\text{eff}} \approx 10$ ppm/K for the VIS to NIR range. For $\lambda_B = 794$ nm, the wavelength shift coefficient is $r = \alpha_{\text{eff}} \lambda_B = 8$ pm/K. For a uniform and weak ($\sim 30\%$ diffraction efficiency) VHG the FWHM spectral bandwidth of the diffracted light, $\Delta \lambda_{\text{FWHM}}$, is inversely proportional to the thickness, $d$, of the VHG [6]. A good analytic approximation for this particular class of material is $\Delta \lambda_{\text{FWHM}} = 0.3 \left(\lambda_B^2 / d\right)$. For a 5 mm thick VHG this gives 38 pm.

Spectral properties of the VHGs are measured with high spatial resolution (better than 0.14 mm) at room temperature prior to the locking experiments. The method is described in [7,8]. The measured local spectral bandwidth is 40+/-3 pm and the typical center wavelength uniformity over the 1.5 x 13 mm clear aperture is better than 20 pm. The spectral output of a spatial multimode diode locked with a VHG is comparable to the spectral FWHM of the VHG. For a diode bar array, the local VHG bandwidth and the uniformity of the center wavelength over spatial changes will determine the spectral output. In the case of high optical powers the small residual optical absorption of the VHG, in combination with non-uniform heat extraction, can lead to temperature gradients within the VHG. The resulting changes in the spectral properties of the VHG can be understood using eq. (3): A temperature gradient along the optical axis would lead to broadening (chirp) of the local spectral VHG bandwidth while gradients perpendicular to the optical axis will reduce the wavelength uniformity. This allows us to distinguish effects from each other. A longitudinal gradient broadens the output of individual emitters while a perpendicular gradient will cause wavelength differences between individual emitters.

Figure 18 shows the variation of FWHM as a function of drive current for the VHG-locked stack with gratings of different diffraction efficiencies. At low drive currents and low output power, the FWHM is very close to the design
bandwidth of the grating, but as operating current increases and the grating is exposed to higher optical power, thermal gradients set-up within the grating contribute to expansion of the FWHM.

Figure 18: FWHM bandwidth (3dB setting on the OSA) of a VHG-locked single-bar stack vs. drive current for VHGs of various diffraction efficiencies

For this DPAL application, FWHM bandwidth in the range of 20GHz (or 40pm) at 780nm (in air) or 780.2nm (vacuum) is desirable. However, these results are very close to the desired specification and demonstrate that with improved VHG design (e.g. increase thickness for reducing FWHM), thermal management and selection of the center wavelength at low power to account for wavelength shift as function of output power, the target specification can be met.

Figure 19: Center wavelength of a VHG-locked single-bar stack vs. operating current with VHGs of various diffraction efficiencies
As shown in Figure 19, center wavelength increases as a function of operating current (equivalent to output power) for all VHG diffraction efficiencies. Little variation is seen across the VHGs, showing a wavelength of ~780.12nm at 15A, and increasing to 780.32nm at 100A.

### 3.4 Wavelength temperature-tuning response of wavelength-locked single-bar stack

In section 3.3, we reported on the center wavelength and FWHM of a VHG-locked stack shift as function of operating power. The total shift of center wavelength from threshold to full operating power of 100W (Figure 17) is 300pm (150GHz) and the shift of spectral FWHM (Figure 18) is 20pm (10GHz). While this is a broad operating range for center wavelength, the DPAL’s center wavelength can vary as a function of operating conditions e.g. the alkali gas pressure, which warrants a more precise control over the center wavelength. To achieve this, one solution is to exploit the wavelength-temperature response of the grating at any fixed operating condition of the pump source by heating the grating. Figure 20 shows the measured response of center wavelength as function of heater temperature with a calculated wavelength-temperature coefficient of 8.4pm/°C. The diode-laser stack was operating at 100W, CW when these results were measured. The shift of center wavelength by heating from 21°C to 55°C is ~280pm or 140GHz. Figure 21 shows the increase in FWHM as a function of heater temperature at a rate of 0.3pm/°C.

![Figure 20: Center wavelength (nm, in vacuum) vs. heater temperature of wavelength-locked single-bar stack](image)

By selecting the correct combination of VHG’s center wavelength and the heating parameters, the optimal operating point can be tuned on demand. For example, if the DPAL’s operating point requires 780.2nm then given the shift of center wavelength of 3pm/W, we can calculate that self-heating of the grating at 100W will result in an increase in center wavelength of 300pm or 0.3nm. Further adjustments for manufacturing tolerances can be made to the VHG’s center wavelength while ensuring that the available tuning range covers the anticipated DPAL operating conditions without the need for excessive tuning of the grating that will deteriorate the FWHM and long term stability of the grating.
To summarize, in this section we have reported on a wavelength-locked single-bar stack, operating at 100W, CW power, without any power penalty due to locking, at center wavelength (in vacuum) of 780.36nm, and FWHM of 0.06nm (or 30GHz). We also demonstrated wavelength-tunability of this stack in the range of 280pm (or 140GHz) at a slight penalty to the spectral bandwidth.

4. **780NM, WAVELENGTH-LOCKED, 3-BAR STACK PERFORMANCE**

4.1 Product Description

To demonstrate power scaling capability with wavelength-locking, we constructed a 3-bar stack (see Figure 22) consisting of a vertically stacked array of individual diode laser bars (described in sections 2 and 3 above) mounted on micro-channel coolers at a bar-to-bar pitch of 1.8mm inside the housing of a standard 30-bar stack offered by DILAS. The stack diodes are collimated in both the fast and slow-axis, with a VHG attached in front of each bar, and an electrical heater attached to the bottom of each VHG for wavelength-temperature tuning. The basic optical layout is same shown for the single bar in Figure 11.

![Figure 22: 3-bar stack with individual FAC, SAC, and VHG (with heater) for each bar](image-url)

\[ y = 0.0003x + 0.0499 \]

\[ R^2 = 0.9267 \]
4.2 Electro-Optical data of a 3-bar stack

Power vs. Current (LI) curve of the 3-bar stack with and without wavelength-locking is shown in Figure 23. Far-field divergence (full width, 90% power content) of fast and slow-axis is shown in Figure 24.

Figure 23: Optical output power vs. drive current for free-running and wavelength-locked stack.

Figure 23 shows at 100A operating current, the free-running stack delivers output power of ~275W and the wavelength-locked stack delivers output power of ~225W, or a power loss of ~18%. It is important to explain that this power loss was not due to the VHG but unfortunately due to failure of emitters on two of the three bars during the VHG alignment and attachment process, with one bar losing 50% of its initial output power. With such a small same size and new assembly procedure for the stack, we do not yet know if these are isolated or systematic failures. While the cause of these emitter failures are not yet understood, we are working to determine whether they are a result of current assembly processes or characteristic of unknown limitations in prototype diode or VHG material we currently have in-house.

In Fig. 24, the relatively low fast-axis divergence of 4.8mrad (90% power content) can be attributed to the low-smile (≤1µm peak-to-valley) on each of the bars. Note that these are 3mm cavity length bars and achieving low smile on micro-channel coolers is difficult. The slow-axis divergence, which is impacted by many factors such as operating current (or current density), base temperature, emitter width and focal length of the SAC lens array, was within our expectations. Although not implemented in these proof-of-concept experiments, further reductions in slow-axis
divergence are possible with optical beam-shaping after the VHG. These shaping techniques can reduce slow-axis divergence at the cost of slightly larger beam in the slow-axis direction.

### 4.3 Spectral response of wavelength-locked 3-bar stack

Each bar in the stack was individually aligned to a VHG with diffraction efficiencies of 6.3%, 9.4% and 12.3%, respectively. Note that the overall linewidth of the stack is limited by the linewidth contributions of the individual bars, which is this case was highest for the 9.4% diffraction efficiency grating (see figure 17). Further, as shown in Figure 18, each VHG has slight variations in the center wavelength, hence the ensemble’s center wavelength and FWHM also increase due to these variations. Finally, any residual VHG heating (e.g. thermal crosstalk between diodes or VHG heaters) will also shift the spectrum and increase the line width.

Figure 25 shows a spectral plot of the wavelengthlocked stack before temperature tuning of the VHG’s to reduce the overall spectral line width. The prominent side-peak on the right is caused by higher center wavelength for Bar 2 while under operation at 100A. (Bar 2 was paired with the 9.4% reflective VHG, which recall has the highest spectral line width-FWHM of the three experimental VHG’s.) The OSA resolution setting of 0.05nm per division emphasizes the peak separation of ~0.1nm.

![Figure 25: Spectrum of wavelength-locked 3-bar stack. Center wavelength is 780.4608nm (vacuum), FWHM is 0.0741nm (each division on the horizontal axis is 0.05nm)](image)

#### 4.4 Wavelength-temperature tuning response of 3-bar stack

Before wavelength-temperature tuning the stack, the side-peak shown in Figure 25 was eliminated by selectively heating the lower wavelength bars and red-shifting their wavelengths. Then all bars were shifted together through a total tuning range of 67GHz. As was shown in earlier testing, this tune range in no way represents a ceiling on achievable tuning, but was rather a result of the heating range chosen for this experiment.

Figure 26 shows the optimized output spectrum before and after temperature-tuning through the tune range, Note that this last tuning experiment employed a constant heating offset across all VHG’s. While this is the simplest heating scheme to implement from a control standpoint, it is possible to employ more complicated schemes that take into account the unique heating characteristics of each VHG/heater pair. We anticipate continuing this work in future studies.
Figure 26: Left plot shows the spectrum of the wavelength-locked 3-bar stack, heating optimized before wavelength-temperature tuning. Center wavelength is 780.5573nm (vacuum) and FWHM is 0.0811nm. Right plot shows the spectrum shifted to 780.6993nm (vacuum) and FWHM is 0.0833nm by heating all VHGs by a constant value.

5. SUMMARY AND CONCLUSIONS

We presented electro-optical and life test results of 3mm cavity length, 18%FF, diode lasers bars at 780nm, 100W, CW output power mounted on micro-channel coolers. Initial results demonstrate reliable optical power at 80W, CW power level. We reported on a narrow-line width, tunable, single-bar stack, with CW output power of 100W at 780.36nm and spectral line width of 0.06nm FWHM (~30GHz), with tunable wavelength-temperature range of 0.28nm (~140GHz). Far-field divergence (full width, 90%power) of the single-bar stack in fast and slow-axis was 3.1mrad and 21mrad respectively. We scaled the single-bar stack and its salient features to a 3-bar stack with CW output power of 225W (average power of 75W/bar) at 780.43nm, line width of 0.0741nm FWHM (37GHz) and demonstrated tune range of 0.14nm (67GHz). Far-field divergence (full width, 90%power) of the 3-bar stack in fast and slow-axis was 4.8mrad and 25mrad respectively. This work demonstrates the technology for developing kW class DPAL pump source which can enable the DPAL to realize its full potential.

6. ACKNOWLEDGEMENTS

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7. REFERENCES