Narrow line diode laser stacks for DPAL pumping

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ABSTRACT

Diode pumped alkali metal vapor lasers (DPALs) offer the promise of scalability to very high average power levels while maintaining excellent beam quality, making them an attractive candidate for future defense applications. A variety of gain media are used and each requires a different pump wavelength: near 852nm for cesium, 780nm for rubidium, 766nm for potassium, and 670nm for lithium atoms. The biggest challenge in pumping these materials efficiently is the narrow gain media absorption band of approximately 0.01nm.

Typical high power diode lasers achieve spectral widths around 3nm (FWHM) in the near infrared spectrum. With state of the art locking techniques, either internal to the cavity or externally mounted gratings, the spectral width can typically be reduced to 0.5nm to 1nm for kW-class, high power stacks. More narrow spectral width has been achieved at lower power levels. The diode’s inherent wavelength drift over operating temperature and output power is largely, but not completely, eliminated. However, standard locking techniques cannot achieve the required accuracy on the location of the spectral output or the spectral width for efficient DPAL pumping. Actively cooled diode laser stacks with continuous wave output power of up to 100W per 10mm bar at 780nm optimized for rubidium pumping will be presented. Custom designed external volume holographic gratings (VHGs) in conjunction with optimized chip material are used to narrow and stabilize the optical spectrum. Temperature tuning on a per-bar-level is used to overlap up to fifteen individual bar spectra into one narrow peak. At the same time, this tuning capability can be used to adjust the pump wavelength to match the absorption band of the active medium. A spectral width of <0.1nm for the entire stack is achieved at >1kW optical output power. Tuning of the peak wavelength is demonstrated for up to 0.15nm. The technology can easily be adapted to other diode laser wavelengths to pump different materials.

Keywords: High power diode laser, DPAL, VBG, VHG, narrow line, spectral width, wavelength locked, defense

1. INTRODUCTION

In order for high energy lasers to be widely deployed, systems have to become smaller and more efficient compared to the high energy lasers available today. In 2003 W. F. Krupke et al. proposed a type of optically pumped gas laser for directed energy, the diode-pumped alkali metal vapor laser (DPAL) [1] which has since shown very promising results. However, Shapiro and Teare state that in order to achieve higher power, the efficiency of coupling between the pump laser energy and the chemical cell must be increased [2]. One of the main reasons for inefficient coupling is the difference in spectrum between the diode laser emission and the absorption of the DPAL medium.

Due to the narrow absorption line of alkali metal vapors, pump diodes have to achieve a very narrow spectral width to maintain high efficiencies. According to Perram, the diode spectrum can be wider than the absorption line of the gas without significant penalties in performance if the alkali concentration is increased accordingly [3]. He further states that depending on the DPAL design the diode emission spectrum should be as narrow as 0.02nm (10GHz) for low-pressure gain cells but can be as large as 0.2nm (100GHz) for high pressure gas cells that are operated at about 10 atmospheres and pump rubidium at 780nm.

Free running, high power diode laser bars as used for this work typically have a spectral width of 3nm FWHM. In order to minimize the line width for more efficient pumping of alkali metal vapors, Volume Bragg Gratings (VBGs) are used. These VBGs are mounted in front of each laser bar and are aligned so that they provide wavelength selective feedback into the laser cavity and thus increase the effective gain for only a narrow region of the spectrum. For best possible results the epitaxy-structure, facet reflectivity, and VBG design have to be optimized. Parameters that have been

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optimized for this work are cavity length, laser structure to include the active region and the facet reflectivity of the diode, as well as diffraction efficiency and thickness of the VBG.

Even with optimized VBGs in place, numerous factors influence the spectral width of a high power diode laser stack. A stack is constructed of multiple laser bars. Bar-to-bar center wavelength variations broaden the line width of the ensemble. The center wavelength of each VBG is temperature dependent and feedback will occur at higher wavelength with rising temperatures. At the same time the manufacturing process of the VBGs entails a degree of manufacturing variation leading to a spread of center wavelengths for each bar in the stack. Correcting this through careful grating selection reduces the yield and increases costs significantly. The temperature of the VBG is influenced internally by absorption of optical power and externally by environmental conditions, including temperature and airflow. While the absorption of laser radiation adds a usually undesired shift in center wavelength, this temperature dependency of the feedback wavelength can be used as a tuning mechanism by actively influencing the temperature of the VBG. In an earlier phase of this work the temperature coefficient of the VBG in use has been measured as 0.3 pm/°C as reported by Pandey, et al. [4].

Thermoelectric coolers (TECs) are a common choice for temperature control applications that need to be fast and accurate. However, due to the packing density and small bar-to-bar pitch inside a high power diode laser stack, TECs are difficult to implement as they are usually a few millimeters thick and require a heat sink on the opposite side of the temperature controlled element. Further, the typical efficiency of TEC coolers is about 50% which leads to an increased amount of heat to the system that needs to be dissipated. Finally, if a TEC is used to cool a part, the heat from the part and the inefficiencies of the TEC must be rejected, leading to increased complexity, cost and likelihood of failure.

Resistive heaters, on the other hand, are very thin and efficient, can be manufactured in custom shapes, and do not require an additional heat sink. All of these advantages allow for easier integration into high power diode laser stacks. Due to the fact that the temperature can only be increased but no cooling is available, the center wavelength of the VBGs must be chosen so that even at maximum optical power the resulting center wavelength of the laser bar is lower than the desired pump wavelength. Doing so insures that with some specific heating of each VBG, all laser bars can be tuned so that the output spectra overlap with each other and the absorption band of the pumped gas. At reduced laser power the heaters can be used to compensate for the reduced amount of internal heating of the VBGs due to absorption of laser radiation under standard heat loads, resulting in efficient pumping being maintained across a wide power range.

2. DESIGN

The pump stack is based on DILAS’ industrial grade micro channel coolers. These coolers allow for efficient heat removal with a low thermal resistance. At the same time the small size allows for high packing densities while minimizing system size. Diode laser bars with 19 emitters on a 500µm pitch and an emitter size of 90µm are used. The cavity length is 3mm. Full qualification data for the chip material has been presented by Pandey et al. [4]. The bars can output more than 100W of optical power, but for the scope of this work the bars are operated at a maximum of 80A to maintain a reasonable life time for the program. The optical power at 80A is about 80W at 54% electrical to optical efficiency.

![Figure 1a: High power diode laser stack.](image1)

![Figure 1b: LI curve of 15 bar stack without optics.](image2)
Figure 1 shows a picture of a standard DILAS water cooled stack and the LI curve of the 15-bar stack developed for this program. The LI curve was acquired before any optic is mounted to the stack and represents the base line for all further measurements.

Fast axis and slow axis collimation optics are mounted in front of each laser bar to minimize the divergence, which is known to be a critical parameter in achieving good feedback from the VBG into the laser cavity. FAC lenses are mounted directly to the heat sink of each laser bar, while SAC lenses are affixed to a frame mounted to the front of the stack. A second frame is stacked onto the SAC frame to hold the VBGs.

As discussed above, resistive heaters were selected to control the temperature of the VBGs and allow narrow and broadband tuning of the narrowed spectrum. Therefore, individual heaters are mounted to each individual VBG to tune the wavelength of each laser bar. Custom side plates are added to the stack in order to route the heater wires from the front of the stack to the back while adding mechanical protection to the VBGs after they are mounted (Figure 2a). All 30 heater wires are routed to a common connector in the back of the stack to allow an easy connection to a controller that drives all 15 heaters (Figure 2b).

A custom 15-channel controller was developed to adjust the temperature of each heater (Figure 3a). The controller allows stand-alone operation via front panel controls as well as remote control by software developed for this project (Figure 3b). Individual heaters can be addressed to tune single bars and minimize the spectral width of the ensemble. A ‘master’ setting allows the user to shift all channels together in order to tune the spectrum of the entire stack. This feature can be used to optimize the overlap of diode spectrum and absorption band of the gas. This control is to be engineered to operate under feedback control at a later date.

Figure 2a: Front of 15-bar stack with mounted FACs, SACs, VBGs, and heaters.

Figure 2b: Back of stack with 30-pin connector and electrodes to drive laser bars.

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Figure 3a: 15-channel controller to adjust heater settings.

Figure 3b: Remote control software for heater controller to allow more convenient tuning of all 15 channels.
3. RESULTS

3.1 Power

Figure 4b shows a front view of the finished stack with all optics and heaters mounted. An LI-curve (Figure 4a) of the final stack was acquired at 25°C cooling water temperature. 1kW of optical power was achieved at 76.3A operating current and a voltage drop across the stack of 28.5V. This leads to an electrical-to-optical efficiency of 46.0%. The drop in power compared to the initial test shown above can entirely be explained by emitters that failed over the course of the build and rigorous testing of the stack. Initial data for a similar setup presented earlier by Pandey, et al. proves that no significant power loss is introduced by wavelength stabilization with the VBGs [4].

A two hour long burn-in was conducted at 50A operating current and 23°C cooling water temperature to test the thermal stability of the system. All 15 heaters were set to their pre-determined values to minimize the spectral width of the entire stack while matching the target wavelength for this program. The output power was stable within the accuracy of the power detector used for the test. An increase of about 5W was measured when lowering the water temperature to 18°C - an expected effect due to an increase in diode efficiency at the lower junction temperature.

3.2 Beam parameters

15 individual laser bars are stacked vertically with a bar-to-bar vertical pitch of 3.6mm. Each bar has an emission height of < 1mm (about 0.9mm for 90% power content). This leads to a total beam height of 51.5mm. The vertical fill-factor is approximately 30%. This leaves room for spatial interleaving of multiple stacks as described by Bachmann [5] which can double the overall power while maintaining roughly the same beam size and divergence, hence increasing the brightness of the stack. In the horizontal direction the beam is about 10mm wide. The beam is comprised of 19 emitters per laser bar; the focal length of the SAC is chosen so that gaps between emitters are mostly eliminated.

Figure 5: Far field intensity distribution of the full stack in the vertical (fast axis) direction and horizontal direction (slow axis).
FAC and SAC lenses are used to collimate the emission of the stack in both the vertical and the horizontal axis. In the fast axis direction the resulting divergence is 4.6mrad (90% power content). In the slow axis direction the divergence is 21mrad (90% power content). Beam profiles for both axes are shown in Figure 5.

3.3 Spectral line width

Due to manufacturing tolerances of the VBGs, all bars vary slightly in center wavelength after VBG alignment. At the same time a variation in output power between bars may lead to different VBG temperatures due to absorption of optical power. Heaters mounted to each VBG are used to compensate these effects. In order to achieve the narrowest line width possible, all 15 heaters in the prototype design are adjusted individually to tune the bar spectra until they overlap. Figure 6 shows the spectrum of the entire stack at 600W and 1kW optical power. Heaters were tuned at 50A only and not re-adjusted at 80A. Due to variations between bars, the wavelength difference between 50A and 80A was not precisely the same for all bars. This leads to an increase in spectral width at 80A that could likely be eliminated by further adjusting the heater settings at this drive current. For future builds it is planned to tune the heaters at various power levels to create a lookup table that can be programmed into the heater controller, with the intent of leading eventually to a feedback-based, auto-tuning stack.

A 3dB spectral line width of 0.072nm is achieved at 50A. This corresponds to 35.5GHz for a center wavelength of 780nm. At 80A the 3dB line width is measured as 0.083nm or 40.9GHz. No side lobes are present in the profile, indicating good locking performance which is supported by the 95% enclosed power line width of 0.136nm at 50A and 0.166nm at 60A. The center wavelength measured in vacuum is 780.246nm at 50A and 780.293nm at 80A which results in a wavelength drift of about 45pm for an increase in optical power of 400W.

![Figure 6a: Spectrum of the stack at 50A (about 600W).](image)

![Figure 6b: Spectrum of the stack at 80A (about 1030W).](image)

3.4 Wavelength tuning

Due to the wavelength shift of the locked spectrum with output power, the capability to tune the emission spectrum is desired to compensate for this shift. At the same time, this allows tuning the emission spectrum for maximum absorption by the active medium. A ‘master’ channel is used in the heater controller to create an offset to all 15 VBGs, thus allowing the shifting of the spectrum of the stack ensemble changing but a single input value. This allows the wavelength to be tuned both longer (red shift) and shorter (blue shift). The minimum wavelength that can be achieved is determined by the cold cavity VBG resonance. The upper spectral limit is determined by the maximum temperature the VBGs and mounting features can accept without distortions that impact the optical performance. Other limitations might be set by the control electronics and the maximum rating of the heaters. For data shown here, a heater temperature of about 40°C was chosen for the upper limit.

Figure 7 shows spectra of the entire stack at various heater settings. The stack was operated at 50A (600W) for all tests. From left to right the first spectrum is acquired with all heaters turned off. Due to manufacturing tolerances of the VBGs and laser bars, not all individual bar spectra overlap which explains the wider spectrum relative to the other three. The third spectrum from the left (Optimum) shows individually tuned heaters for best overlap of individual bar spectra. The second (blue shift) and fourth (red shift) spectra show the lower and upper limit of the tuning range tested here. Only the ‘master’ was adjusted on the heater controller which adds an offset to all 15 channels. This simple approach to the
‘master’ setting typically leads to increased line widths across the tuning range as not all heaters may have the same tuning behavior. A lookup table programmed into the controller easily resolves the problem similar to the lookup table for various optical power levels discussed above.

With all heaters turned off, the 3dB spectral width of the entire stack is 0.11nm (54.2GHz). The 95% enclosed power line width is 0.23nm (113.3GHz). At the optimum with all heaters tuned properly the 3dB spectral width is reduced to 0.072nm (35.5GHz). The 95% enclosed power line width is reduced to 0.14nm (69.0GHz). The center wavelength is adjusted from 780.174nm (blue shift) to 780.329nm (red shift). This leads to a tuning range of 0.155nm or 76.4GHz.

3.5 Stability
For all experiments shown here the stack was operated in a table top environment without an external enclosure. A one hour long stability test has been conducted at 50A (600W). Figure 8 shows logged data for cooling water temperature, air temperature, optical power, center wavelength, and spectral width. The fluctuation in the water temperature is caused by the PID controller of the chiller. The power output is affected by the water temperature and it can be seen in the graph that both signals vary at the same frequency. The total variation in central wavelength from minimum to maximum recorded over the one hour test period is 0.019nm.

Figure 8: One hour stability test. Water temperature fluctuations cause optical power to vary at the same frequency.
After the burn-in, the cooling water temperature is intentionally changed to measure the effect of the water temperature on the wavelength and optical power. As described above the power increases by about 5W when dropping the water temperature from 23°C to 18°C. This increases the amount of heat absorbed by the VBGs slightly which suggests a shift of the spectrum to longer wavelength. However, data shows that the center wavelength actually shortens with lower water temperature. While not fully investigated, it is believed that a thermal path from the VBGs to the cooling water exists which cools the VBGs more than the extra heat introduced by the increase in optical power. The spectral width is also affected by the change in water temperature and the spectrum is narrower for lower water temperature and wider at elevated temperatures. Heater settings have not been optimized at either the lower or the higher water temperature which prevents a full analysis of the change in spectral width. Over this range of temperature swing, it is unknown whether individual bar spectra are affected in their line width or only in their center wavelength. Both have an effect on the spectral width of the ensemble.

4. SUMMARY

A 15-bar high power diode laser stack that is optimized for narrow line DPAL pumping has been presented. The stack is based on DILAS' industry proven micro channel coolers that offer low thermal resistance combined with a small form factor. VBGs are used to narrow the spectrum of each laser bar. Heaters are used to tune the wavelength of all 15 bars individually, overlapping the stack’s spectra with the gain medium and minimizing the spectral width of the ensemble. The heaters can further be used to shift the emission of the entire stack and tune the output for highest absorption of the active medium.

The stack was optimized for rubidium pumping near 780nm. A 3dB spectral width of 0.072nm (35.5GHz) was achieved at 600W optical power. At 1kW optical power the line width was a non-optimized 0.083nm (40.9GHz). A tuning range of 0.155nm or 76.4GHz has been presented without significant impact on the line width of the stack.

Possible planned next steps include an increase in power to 200W per bar, tuning enhancements to the heater controller such as a look up table settings for various power levels and center wavelengths, and possibly closed loop controls for all heaters. The technology can be transferred to other wavelengths and product lines. Pump modules for hyperpolarized noble gases which also have demanding wavelength requirements similar to DPAL are currently in development.

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