ABSTRACT

Due to their low quantum defect, diode pumped alkali metal vapor lasers (DPALs) offer the promise of scalability to very high average power levels while maintaining excellent beam quality. Research on DPALs has progressed to ever increasing power levels across multiple gain media species over the last years, necessitating pump power in the kW range. Each material requires a specific pump wavelength: near 852nm for cesium, 780nm for rubidium, 766nm for potassium, and 670nm for lithium atoms. The shorter pump wavelength below 800nm are outside the typical wavelength range for pump diodes developed for diode pumped solid state lasers (DPSS).

The biggest challenge in pumping these materials efficiently is the need for maintaining the narrow gain media absorption band of approximately 0.01nm while greatly increasing power. Typical high power diode lasers achieve spectral widths around 3nm (FWHM) in the near infrared spectrum, but optical gratings may be used internal or external to the cavity to reduce the spectral width. Recently, experimental results have shown yet narrower line widths ranging from picometers at very low power levels to sub-100 picometers for water cooled stacks around 1kW of output power.

The focus of this work is the development of a fiber-based pump system for potassium DPAL. The individual tasks are the development of high power 766nm chip material, a fiber-coupled module as a building block, and a scalable system design to address power requirements from hundreds of watts to tens of kilowatts. Results for a 3kW system achieving ~30GHz bandwidth at 766nm will be shown. Approaches for power-scaling and size reduction will be discussed.

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

1. INTRODUCTION

As outlined in the 2015 Directed Energy Summit Report by Booz Allen Hamilton, diode pumped alkali lasers (DPAL) are considered one of the most promising missile defense laser technologies for achieving the hundreds of kilowatt power levels while still maintaining good beam quality [1]. One of the main benefits of DPAL compared to other lasers is the low quantum defect, resulting in higher efficiency and lower waste heat. At the same time, the gaseous nature of the gain medium allows convective heat removal from the laser cavity.

A major impediment in achieving these powers remains the pump diodes themselves. Pump diodes for DPAL require the spectral width as narrow as the absorption band of the alkali atoms. According to Perram [2], depending on the DPAL design, the diode emission spectrum could be as narrow as 0.02nm (10GHZ) for low-pressure gain cells and as wide as 0.2nm (100GHz) for rubidium gas cells that are operated at about 10 atmospheres of pressure.

In 2014, DILAS introduced high power diode laser stacks at 780nm with optical power exceeding 1kW while maintaining a spectral width (FWHM) of <85pm [3]. Due to size constraints and efficiency considerations, resistive heaters were used to temperature tune the Volume Bragg Gratings (VBGs) used to lock the diode wavelength which resulted in a wavelength tuning range of 155pm. The tuning capability was used to first overlap all individual bar spectra within the stack and then to allow fine-tuning of the wavelength of the entire stack with respect to the absorption peak of the gas.

Improvements in thermal management which minimized thermal gradients inside the gratings in conjunction with improved, closed loop control electronics allowed the reduction of spectral line width to 61pm (FWHM) for a fiber coupled diode laser module operating at 400W output power from an 800μm core fiber [4]. Fiber-based beam delivery
systems are very flexible and, in particular, during the research phase, advantageous compared to free space beam delivery systems. Once closer to field deployment, water cooled stacks are likely the better choice due to the small size and weight and increased efficiency compared to fiber coupled modules. Both the fiber coupled module and the water cooled stack share core technologies so that new developments on one platform can easily be adapted to the other.

As a continuation of the work presented in 2014 [3] and 2015 [4], the goal of recent efforts is to scale the output power into the multi-kilowatt range, while preserving or improving the very narrow spectral line widths required for DPAL. At the same time, triggered by ongoing research with potassium DPAL, efforts have continued to improve chip material at 766nm. The work presented here is divided into improving chip material at 766nm, the build and test of 400W fiber coupled pump modules at 766nm, and a full system demonstration achieving 3kW of optical power from multiple fiber coupled modules while simultaneously maintaining a spectral line width of less than 30GHz.

The approach taken here to build a robust and scalable system is based on centralized control and monitoring of key laser parameters combined with decentralized microprocessors inside each laser head. The microprocessors maintain individual device calibration, handle communication via a bus interface, and control VBG temperatures by multi-channel PID controllers. This approach allows individual modules to maintain an accurate and stable wavelength, while dividing the system into smaller building blocks that are easier to construct and calibrate as compared to one large laser module. Due to the device-internal calibration, a change in wavelength set point can easily be achieved by sending a command via the RS485 interface. Each laser head then tunes all VBG temperatures to the required temperature for that particular wavelength. Another benefit is the capability of drop-in replacements for each laser module without further calibration of the entire system.

2. 766nm CHIP DEVELOPMENT

Data for 766nm diode laser bars has been presented by DILAS in 2015. Power in excess of 100W per 10mm wide laser bar was achieved using 4mm long resonators and a 50% fill factor [4]. While power goals were achieved with these bars, the threshold current was undesirably high—~44A with VBG, negatively impacting the efficiency at the targeted operating point of 80W. The cavity length of the device has a major impact on the performance of the chip. Benefits of longer cavity lengths are the lower current density inside the bulk material and larger surface area for heat transfer, lowering the device temperature. On the other hand, a longer resonator may increase internal losses, resulting in a higher threshold current. For the current phase of the program, a second generation of diodes has been manufactured using a cavity length of 2mm compared to the 4mm from the first iteration.

Figure 1a: LI curve and efficiency for 2mm and 4mm cavity length 766nm chip material with VBG

Figure 1b: LI curve and efficiency for 2mm and 4mm cavity length 766nm chip material without VBG

Figure 1 shows test data for the 4mm and 2mm cavity chip material. Laser bars were mounted to commercially available micro-channel heat sinks and operated at 25°C water temperature. Each chip type was tested with VBG (Figure 1a) and without (Figure 1b). As these bars are coated with a low reflectivity facet coating (R < 0.5%), the threshold current is very high when used without VBG which leads to low electrical-to-optical efficiencies. Once the VBG is in place, the bar operates at its optimum. A significant improvement in efficiency was achieved by reducing the cavity length from
4mm to 2mm. The threshold current with VBG was reduced from 43.9A for the 4mm cavity bar to 26.4A for the 2mm cavity length bar. Along with improvements in the device design, the slope efficiency improved from 0.84W/A to 1.08W/A, bringing the overall electrical-to-optical efficiency to ~44% at the targeted 80W optical output. Further improvements are expected with further epitaxy and VBG optimization.

3. FIBER COUPLED MODULE AT 766NM

The fiber coupled module is based on the same design presented by DILAS in 2015 for a 780nm module [4]. A total of eight micro channel cooled laser bars are optically combined and coupled into a single 600µm core fiber with a numerical aperture of 0.22. Volume Bragg Gratings (VBGs) are used to narrow the emission wavelength by selectively providing feedback into the laser cavity at the Bragg wavelength. Because the grating is inscribed into the glass, the period is affected by thermal expansion of the glass. Thermo-electric coolers (TECs) are used to temperature tune each VBG to the desired center wavelength, thus minimizing the overall spectral width of the ensemble while maximizing overlap between the diode laser emission wavelength and the absorption line of the alkali atoms. Built-in, closed loop temperature controllers ensure stable operation over a broad range of ambient conditions. Wavelength and temperature calibration at various power levels is maintained by implementation of a microprocessor into the laser module. The same processor is used for communication via a RS485 bus interface. The wavelength set-point can be changed remotely while monitoring important operating parameters by PC.

Figure 2a: Optical power of the fiber coupled module
Figure 2b: Wavelength spectra at various power levels

Figure 2 shows measured data for a representative laser module emitting more than 400W at 766nm from a 600µm core fiber. The spectral line width is below 60pm (<30GHz) at all power levels (Table 1). The center wavelength is very stable across the entire power range. Minor broadening of the spectral line width at higher operating current can be seen. This can be attributed to increased thermal gradients inside the VBG at higher optical power.

<table>
<thead>
<tr>
<th>Operating Current [A]</th>
<th>40</th>
<th>60</th>
<th>80</th>
<th>96</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectra line width (FWHM) [pm]</td>
<td>51.6</td>
<td>52.6</td>
<td>53.2</td>
<td>56.3</td>
</tr>
<tr>
<td>Peak Wavelength [nm]</td>
<td>766.49</td>
<td>766.49</td>
<td>766.48</td>
<td>766.47</td>
</tr>
<tr>
<td>Central Wavelength [nm]</td>
<td>766.49</td>
<td>766.49</td>
<td>766.48</td>
<td>766.47</td>
</tr>
</tbody>
</table>

Table 1: Measured spectral data at various power levels

To confirm the wavelength calibration of the OSA, and to ensure that the pump laser is calibrated for its intended use, a potassium gas cell was heated on a hot plate. The laser center wavelength is then tuned until excitation of the gas is visible through an IR viewer (Figure 3a). The wavelength is then fine-tuned by maximizing the emission from the gas cell. Figure 3b shows a picture of the complete laser module.
A one-hour stability test was performed with the module operated at 420W optical power output from the fiber. The emission wavelength is within about +/- 10pm of the set point after less than 30 seconds. It then takes about 2 minutes to fully stabilize. However, fluctuations are on the order of 5pm, which is small compared to the spectral line width of the laser. Long term fluctuations are on the order of +/- 1pm which could be caused by the PID settings of the controller, external influences, or the wavelength measurement itself. In terms of the targeted application, the stability is sufficient but could be improved.

4. SYSTEM LEVEL RESULTS

The design of the module allows operation of multiple units in a pump system. As described in the module section above, a microprocessor inside each module maintains wavelength calibration settings and controls the temperature of all eight VBGs in order to maintain a narrow spectral line width at the desired emission wavelength. The microprocessor also monitors the diode temperature, humidity inside the laser head, and the proper connection of the optical fiber to the unit. All parameters, including the wavelength set-point, can be monitored or adjusted from a PC using control software developed for this module.

Currently, a total of seven modules have been operated together for a combined optical output power of 3kW. For the experiment, all fiber outputs were pointed at a single power detector similar to the setup shown in Figure 5a. Figure 5b shows the control software interface screen. On the right side of the user interface, module specific information is displayed, including the power monitor reading, the serial number, interlock status, and information about whether all
TEC-temperatures are within the specified range. The left side of the user interface contains parameters relevant to all modules. The wavelength set-point for all units can be changed in the upper left corner. Other indicators include the sum of all power monitors, and the interlock status for all modules.

![Figure 5a: Test setup with 6 modules on a common power detector](image)

![Figure 5b: Control software with tabulated information for all modules and central set-point for wavelength](image)

3kW of optical power were achieved at about 95A and the electrical-to-optical efficiency was 31.5%. The spectral line width stayed very close to the individual module result, indicating good overlap of all seven module spectra. A spectral line width (FWHM) of 58pm (29.7GHz) was achieved- measured at 3kW of optical power after the wavelength had stabilized. Similar to individual module data, no side-modes are present, with a noise limited side mode suppression ratio (SMSR) of at least 25dB.

![Figure 6a: Optical power and efficiency of 3kW pump system consisting of 7 individual fiber coupled modules](image)

![Figure 6b: Combined spectrum of all 7 fiber coupled modules operated at a total optical power of 3kW](image)

The modular approach worked as intended and no wavelength tuning was required at the system level- all individual modules were calibrated during the build process and then performed as expected inside the system. This also indicates that module replacements or the addition of extra modules will be possible without further calibration.

5. SCALABILITY AND SIZE REDUCTION

While current requirements for research applications can be fulfilled with the design as it is, longer term goals for DPAL aim at hundreds of kilowatts of output power. At the same time, lasers need to be mobile or even airborne. This requires the system not only to scale up in power, but also to come down in size and weight.

One important factor in system size weight and power (SWAP) is the efficiency of the laser. Higher system efficiency generally implies higher optical power at the same electrical input. At the same time waste heat is reduced which
positively impacts the cooling system design. While diode efficiency has been significantly improved from data presented last year, the 766nm chip material is still early in its development. With further development efforts it is expected that the efficiency of the chip material can be significantly improved, matching more mature high power diode laser wavelength like 808nm where efficiencies of >60% are commercially available.

In terms of package size, two distinct paths forward can be pursued. The first is the size and weight reduction of the fiber coupled module. While the existing design has not been focused on these aspects, DILAS leads the industry in the development of small, light-weight fiber coupled packages aimed at defense applications [5]. While the design of the DPAL pump modules is more complex than that of pump modules for fiber lasers, similar concepts can be applied, minimizing the size and weight of the module. The second path is to switch from fiber coupled pump modules to free space, stack based pump modules. Most of this technology already exists as presented by DILAS in 2014 [3] and improvements made since, like closed loop temperature control and a modular control architecture, can be applied to water cooled stacks as well. Another benefit of the free-space approach is the higher overall efficiency compared to the fiber coupled module, as fiber coupling losses do not apply.

Either path yields a pump module that can be scaled to very high power pump systems. The modular approach allows very accurate wavelength calibration on a module level. The combination of de-centralized processing power inside each module with centralized control, allows starting with small systems and then adding more and more modules over time. The control software has been developed with scalability in mind and automatically detects the number of connected laser modules while adding control elements to the user interface for each module.

6. SUMMARY

A fiber coupled high power diode laser DPAL pump system with 3kW of optical output power from multiple 600µm core fibers and spectral line width of <60pm (<30GHz) at 766nm has been demonstrated. The system is comprised of seven fiber coupled modules with very low spectral line width of about 56pm. The wavelength is stable within +/- 1pm over the course of 1 hour. Scalability is achieved by use of a modular approach with de-centralized microprocessor control inside each laser module, combined with a central PC-based control interface. In order to enable research on potassium based DPAL, second generation chip material at 766nm has been qualified, with each 10mm wide laser bar rated at 80W output power while achieving an electrical-to-optical efficiency of about 44% at that power level. Development efforts at that wavelength are ongoing and further improvements in power and efficiency are expected.

The technology shown can be adapted to other available high power diode laser wavelengths. A path forward to very high output powers while minimizing size and weight has been discussed. Concepts developed at DILAS for light-weight fiber-laser pump modules can be applied to the DPAL pump module, or the closed-loop temperature controlled VBG technology can be adapted to high power water cooled stacks, which have higher efficiency and lower SWAP compared to fiber coupled modules. There is no principle barrier to scaling the technology to 10s or even 100s of kilowatts of output power.

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REFERENCES


