High power 7-GHz bandwidth external-cavity diode laser array and its use in optically pumping singlet delta oxygen

Lei S. Meng, Boris Nizamov, Pratheepan Madasamy [i], Jason K. Brasseur [ii], Tom Henshaw, and David K. Neumann

Directed Energy Solutions, 890 Elkton Dr. Suite 101, Colorado Springs, CO 80907
[i]Pratheepan Madasamy is currently at Fibertek inc., email: pmadasamy@fibertek.com
[ii]Jason K. Brasseur is currently at S2 Corporation, email: brasseur@s2corporation.com
leim@denergysolutions.com

Abstract: Using a 14-mm thick volume Bragg grating, spectral bandwidth of a cw-operated diode laser array is narrowed to 7 GHz (FWHM). Total output power reaches 13.5 W cw, of which 86% is in the 7-GHz band. With such a narrow bandwidth, it is possible to temperature tune laser frequency across O_2 $X^3\Pi \rightarrow b^1\Sigma^+$ absorption line at 763.8 nm, efficiently generating $O_2(^1\Delta)$ molecules.

© 2006 Optical Society of America

References

1. Hidemi Tsuchida, "Tunable, narrow-linewidth output from an injection-locked high-power AlGaAs laser diode array," Opt. Lett. **19**, 1741 (1994).
2. Stuart MacCormack, Jack Feinberg, and M. H. Garrett, "Injection locking a laser-diode array with a phase-conjugate beam," Opt. Lett. **19**, 120 (1994).
3. B. Chann, I. Nelson, and T. G. Walker, "Frequency-narrowed external-cavity diode-laser-array bar," Opt. Lett. **25**, 1352 (2000).
4. F. Wang, A. Hermerschmidt, H. J. Eichler, "Narrow-bandwidth high-power output of a laser diode array with a simple external cavity," Opt. Commun. **218**, 135 (2003).
5. C. Moser and G. Steckman, "Filters to Bragg About," Photonics Spectra, June 2005, p. 82.
6. B. L. Volodin, S. V. Dolgy, E. D. Melnik, E. Downs, J. Shaw, and V. S. Ban, "Wavelength stabilization and spectrum narrowing of high-power multimode laser diodes and arrays by use of volume Bragg gratings," Opt. Lett. **29**, 1891 (2004).
7. Yujin Zheng and Hirofumi Kan, "Effective bandwidth reduction for a high-power laser-diode array by an external-cavity technique," Opt. Lett. **30**, 2424 (2005).

High power diode laser arrays (DLAs) produce high laser power with high efficiency and long lifetime. However, when free running, they have wide spectral bandwidths of 2 nm (~ 1 THz) or more. For many applications, such a bandwidth is often too broad. A number of approaches have been explored to narrow the bandwidth of the DLAs. The first approach is injection-locking from an external master laser [1,2]. This approach gives output bandwidth at sub-MHz level but requires complicated optical alignment. The second approach employs wavelength-selectable external cavity. Using planar dispersive gratings in Littman-Metcalf or Littrow configurations to provide optical feedback to DLAs has been investigated [3,4]. However, optical alignment is still tricky in these approaches; optical feedback has low efficiency; and whether the gratings can withstand high laser intensity is questionable.

The volume Bragg grating (VBG) receives many attentions recently [5]. The grating contains Bragg planes of varying index of refraction in a bulk of photosensitive glass. This VBG operates as a narrow-band spectral filter: when this element is placed in front of a DLA, a narrow portion of the laser emission spectrum is reflected back (see Fig. 1). This self-

injection will force the DLA to lase at the injected wavelength determined by the VBG. This device is called a VBG-based external-cavity diode laser array (ECDLA). Volodin, *et al.* [6] first reported the effectiveness of this method. Zheng *et al.* [7] reported that their VBG-ECDLA reached 0.24 nm FWHM bandwidth and 20 W output power.

In this paper, we report a unique VBG-ECDLA where the DLA's bandwidth is reduced to 7 GHz (0.0136 nm) FWHM. This is more than two orders of magnitude reduction from DLA's free-running bandwidth. Maximum power reaches 13.5 W and ~ 86% of total power is in the 7-GHz band.

Development of this VBG-ECDLA was motivated by the need of a robust, compact and efficient laser source to generate $O_2(^1\Delta)$ molecules, frequently called Singlet Delta Oxygen (SDO) molecules. High-power chemical oxygen-iodine lasers (COIL) use energy transfer from SDO molecules to iodine atoms to generate population inversion on iodine atom spin-orbit transition. SDO is also highly reactive towards biological and chemical agents and can be used for bio/chem decontamination. We demonstrate that our VBG-ECDLA device has narrow bandwidth and tunable wavelength and can be used to optically pump oxygen molecules.

Figure 1 shows the overview of VBG-ECDLA. The DLA, manufactured by nLight Photonics, Inc., has center wavelength at around 760 nm. It is comprised of 19 emitters each with facet size of 150 μm and spaced 500 μm apart. The emitters' front facets are anti-reflection (AR) coated to about 0.5% reflectivity. A cylindrical microlens and a cylindrical microlens array are attached in front of the DLA for collimating the beam on fast-axis and slow-axis respectively (FAC and SAC). The VBG, made by Ondax, Inc., has a physical dimension of 13×3×14 mm. The thickness of 14 mm results in a narrow reflective bandwidth of ~ 0.013 nm (~7 GHz). The reflection band is centered at 763.8 nm and the reflectivity is about 25%. The light-passing surfaces on microlenses and VBG are all AR coated.
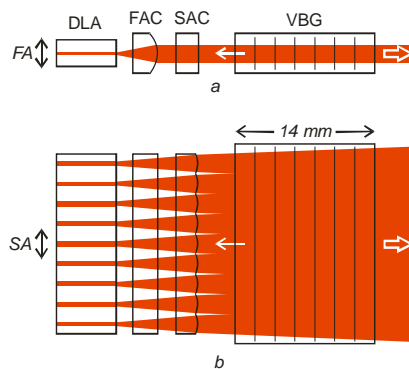

Fig. 1. Structure of external-cavity diode laser array (ECDLA). A volume Bragg grating (VBG) is used to provide narrow-band optical feedback to a diode laser array (DLA). Between the VBG and DLA, a fast-axis collimating (FAC) microlens and a slow-axis collimating (SAC) microlens array are used for beam collimation. (a) and (b) are views into fast-axis (FA) plane and slow-axis (SA) plane, respectively.

The VBG is mounted on a modified Newport mirror mount and it can be aligned by finely rotating around the DLA's slow-axis and fast-axis. VBG is thermoelectrically cooled with temperature stability of ± 0.01°C. Later, it will be shown that this is how the laser's frequency can be precisely controlled. The DLA is manufactured in a conduction-cooled "CS" package. The CS package is then mounted on a bigger water-cooled heat sink. All the data in this paper are taken when the water-cooled heat sink is maintained at 10°C. This passive conduction cooling forms a temperature gradient from DLA to heat sink. For example, at 40-A driving current, temperature of DLA is measured to be 28°C when free running. It is also noted that the DLA's temperature increases as the current increases.

For most effective bandwidth-narrowing, the DLA's each emitter should receive light reflected from the VBG with equally high efficiency. However, because of the so-called

"smile" effect (the emitters are not aligned perfectly straight), VBG coupling conditions to each emitter are different. This causes the fact that some emitters have good side-mode suppression while others do not. To evaluate overall spectral quality of the ECDLA, an integrating sphere was used to collect all the light and an optical fiber couples the integrating sphere output into an optical spectrum analyzer (OSA). The OSA measures the spectrum as shown in Fig. 2(a).
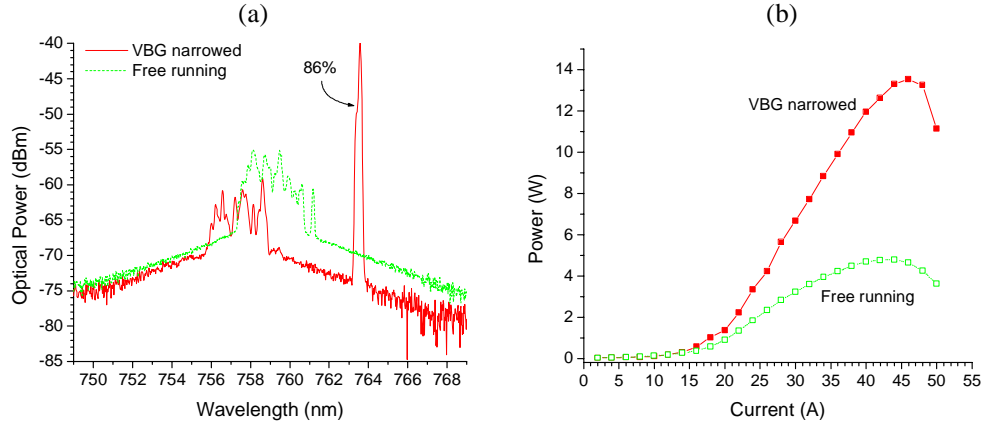
(a) (b)

Fig. 2. (a) Laser output measured by an optical spectrum analyzer. The red solid curve is with VBG and about 86% of total power is within the narrow-band emission near 764 nm; the green dotted curve is free-running without VBG. The DLA is operated at 40 A. (b) Optical power as a function of current. The red solid squares are the powers of VBG-narrowed DLA; the green hollow squares are the powers of free-running DLA.

In Fig. 2(a), the DLA's free-running spectrum is shown as green dotted curve and it shows wide emitting spectrum centered at ~759 nm. When the VBG is appropriately aligned in front of the DLA, the wide-band free-running light is suppressed and a narrow-band emission is measured near 764 nm determined by VBG's center wavelength. There are still some remaining wide-band emissions from 756 to 759 nm but the power is 19 dB lower than the narrow-band peak. By calculating the area covered by the curve, we conclude that ~86% of total power is within the narrow band emission. We believe that this imperfect spectrum is due to imperfect coupling between VBG and some emitters caused by "smile" effect discussed earlier. We also note that the wide-band emission shifts wavelength from free-running condition to VBG-narrowed condition, this is because temperature of the DLA is different in two cases. At 40A, temperature of the free-running DLA is about $28^{o}C$, while the VBG-narrowed DLA is about $2^{o}C$ lower because more optical power (therefore less heat) is generated.

Figure 2(b) shows ECDLA's output power measured as a function of driving current (red data). Maximum power of 13.5 W is measured at the driving current of 45 A. At current higher than 45 A, thermal roll-over effect starts and output power drops due to high temperature (~$30^{o}C$) of the DLA. The green data are the DLA's free-running power without using VBG. It is lower because of the AR coating on the emitters' front facets.

Although Fig. 2(a) shows a narrow-band emission measured by OSA, the true bandwidth of the ECDLA is still unknown due to the limited resolution bandwidth (0.08-nm) of the OSA. Therefore, we build a scanning Fabry-Perot interferometer for identifying the ECDLA's bandwidth. The FP interferometer uses two plane mirrors parallel to each other and spaced 6-mm apart (free spectral range = 25 GHz). A single-mode external-cavity diode laser (linewidth < 1 MHz) is used to align and characterize the interferometer. The finesse is measured to be ~26, which means that the spectral resolution is about 1 GHz. Fig. 3 shows the interferometer-transmitted signal of the ECDLA as the interferometer's length is scanned. It measures the ECDLA's bandwidth to be ~7 GHz FWHM, which is the same as the VBG's bandwidth (~0.013 nm) resulted from its 14-mm thickness.
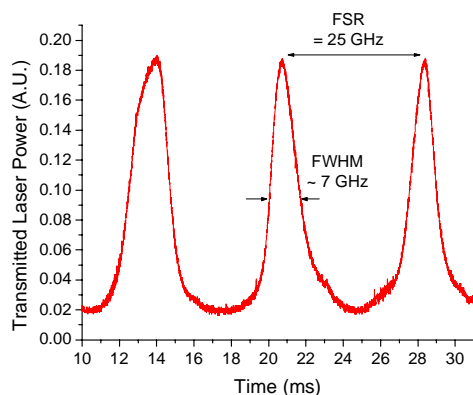
Fig. 3. Transmitted ECDLA signal from a scanning Fabry-Perot interferometer. The interferometer has free spectral range (FSR) of 25 GHz and spectral resolution of 1 GHz. The ECDLA bandwidth is measured to be ~7 GHz FWHM.

The VBG-ECDLA's lasing wavelength is determined by VBG's reflection wavelength, which can be fine-tuned by temperature. A tuning rate of 0.0064 nm/^{o}C (≈3.3 GHz/^{o}C) is measured by recording the OSA's reading and the VBG's temperature (see Fig. 4).
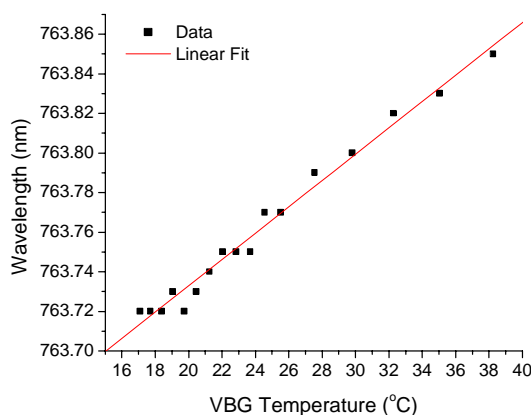

Fig. 4. Temperature tuning characteristics of VBG-ECDLA. Linear fitting gives a tuning rate of 0.0064 nm/^{o}C, or 3.3 GHz/^{o}C.

The VBG-ECDLA's beam quality is evaluated. The beam propagation factor, M^2, is measured to be ~1100 on the slow axis and ~1 on the fast axis. The poor beam quality on the slow-axis is normal for the broad-area diode laser arrays. Fortunately in this paper beam quality is not a critical requirement for our application.

As stated earlier, the purpose of developing this VBG-ECDLA is to optically pump molecular oxygen and generate SDO molecules. Direct optical excitation on X→a transition is not practical because of the small oscillator strength; however a stronger X→b transition can be used. The collisions of optically generated $O_2(b^1\Sigma^+)$ molecules with other molecules generate SDO molecules with almost unit efficiency. For optical pumping, the rotational line at 763.8 nm is chosen because of its strongest absorption at room temperature. This rotational line has FWHM bandwidth of 3.2 GHz under room temperature and 0.2-atm partial pressure. Hence, the VBG-ECDLA device was designed and manufactured at 763.8 nm. Fig. 5 shows the experimental setup for optical pumping and detection of SDO. Pump light is coupled into a multimode fiber (only ~200 mW light is coupled but this is enough for generating detectable

amount of SDO molecules). Fiber output is collimated and then double-passed in a glass cell. SDO is detected by its fluorescence near 1270 nm on a→X 0-0 band. The fluorescence is collected at a direction perpendicular to the laser beam and measured by a Princeton Instruments OMA V spectrometer. The background scattering signal is first collected when the cell is evacuated; the fluorescence signal is then measured after the cell is filled with pure oxygen at the pressure of one atmosphere. Finally the background is subtracted from the fluorescence signal.
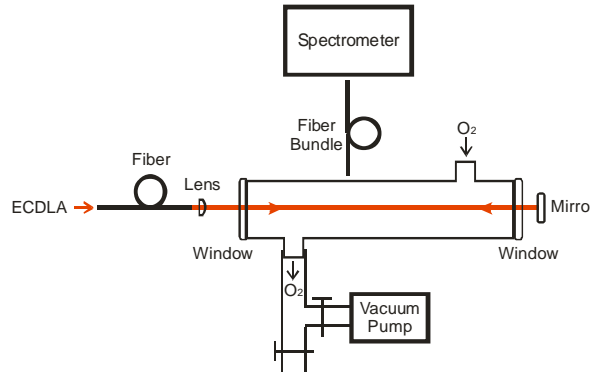

Fig. 5. Experimental setup for pumping and detecting singlet delta oxygen. A fiber bundle collects fluorescence photons of SDO at 1270 nm measured by a spectrometer.

SDO fluorescence spectra are measured as the ECDLA's wavelength is temperature-tuned. Fig. 6 shows how the laser induced fluorescence signal changes when laser's frequency is tuned across the oxygen absorption line. The FWHM line width is measured to be ~10 GHz as expected [approximately the sum of the oxygen absorption linewidth (~3 GHz FWHM) and the ECDLA's bandwidth (~7 GHz FWHM)].
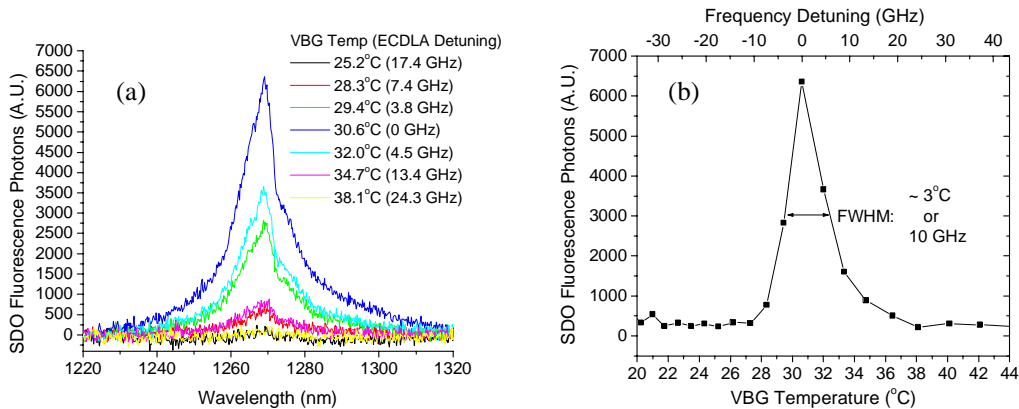

Fig. 6. (a) SDO fluorescence spectra at different VBG temperatures or laser frequencies. (b) The spectra peaks are plotted as a function of the VBG temperature or laser frequency detuning. The FWHM linewidth is about 3°C, equivalent to 10 GHz.

In summary, in this paper we report a diode laser array linewidth-narrowing technique using the volume Bragg grating. Because of the use of a thick VBG, low smile DLA, and high quality AR-coating on the emitters' front facets, a bandwidth of 7-GHz from ECDLA is achieved. To our knowledge, this is the narrowest bandwidth achieved in the DLA bandwidth-narrowing technique. Total output power of our ECDLA reaches 13.5 W cw, of which 86% is in the 7-GHz lasing band. Laser's frequency can be conveniently tuned by changing the temperature of the VBG at a rate of 3.3 GHz/^{o}C. With this narrow bandwidth and tunability,

we successfully tune the laser's frequency across an absorption line of oxygen. To obtain higher output power, more effective cooling of the DLA is desired; for example, placing DLA in a microchannel water-cooled package. Low operating temperature not only eliminates the thermal roll-over effect, it also helps increase the lifetime of DLA. To further improve power percentage in the narrow band, lower smile DLA is required in the diode array manufacturing. The motivation of developing this VBG-ECDLA is to optically pump singlet delta oxygen for decontamination purpose. However many other applications are foreseen, such as efficiently pumping solid-state lasers, laser remote sensing, and military applications.

Acknowledgments