Wavelength-tunable narrowband high-power diode laser stacks based on volume Bragg grating™ technology

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Abstract: We present a novel approach to achieving both wavelength stabilization and wavelength agility in high-power two-dimensional stacks of high-power laser diodes. This approach utilizes volume Bragg gratings with Bragg period that varies as a function of position within the clear aperture of the element according to a periodic function with period equal to the spacing between the laser diode bars within the stack. The Bragg period varies linearly within each period so that translation of the volume Bragg grating element results in simultaneous tuning of the wavelength of all the bars in the stack. As a result, the wavelength of the stack is adjustable, stable and the emission line is narrowed to < 0.5 nm. This kind of laser diode stacks is particularly suitable for pumping of gaseous media with very narrow absorption lines, e.g. atomic vapors of rubidium, cesium, potassium etc.

Keywords : Diode lasers, Diode laser arrays, Volume holographic gratings, Diode laser tunable stacks, Narrow bandwidth

1. INTRODUCTION

Among different classes of lasers that are scalable to high output power (> 10 kW cw) without deterioration of mode quality (i.e. preserving nearly diffraction-limited beam quality) alkali vapor lasers are in a class of their own. One of their clear advantages is extremely low quantum defect (e.g. rubidium vapor lasers are pumped at 780 nm and emit at 795 nm resulting in < 2% quantum defect) that leads to generation of very little heat inside the medium. Another advantage is a very low thermo-optical coefficient of the active gas medium that results in minimal thermal lensing even with very high optical pump powers.

High mode quality and excellent optical efficiency of the alkali-vapor lasers have been demonstrated with Ti:sapphire lasers used as an ideal pump [1, 2]. However, full advantages of these lasers can only be realized when high-efficiency, low cost pump sources can be employed for pumping. The ideal pump source for these lasers would a stack of high-power laser diodes. Continuous progress with high-power semiconductor lasers has lead to improvements in laser diode efficiency and better heat management of packaged devices. However, their fundamental drawback for pumping of gas media with extremely narrow absorption lines is the line width, accuracy of the wavelength and its stability against temperature.

Fortunately, the use of the volume Bragg grating (or VBG™) technology has been shown to be a simple and effective way to overcome all of these drawbacks of the high-power laser diodes [3, 4]. It leads to approximately an order of magnitude reduction in line width of laser diodes, almost equal improvement in wavelength accuracy and approximately 30 times improvement in thermal drift coefficient.

At the same time, the VBG™ elements do have center wavelength accuracy tolerance that is necessary to maintain in order to keep the manufacturing costs of these elements down. Moreover, when high optical pump powers are transmitted through VBG elements, such as those emitted by high-power laser diode stacks, a certain amount of light, however minimal, is absorbed by the VBG, collimating lenses and the surrounding mounting

High-Power Diode Laser Technology and Applications V, edited by Mark S. Zediker,
Proc. of SPIE Vol. 6456, 645614, (2007) · 0277-786X/07/$18 · doi: 10.1117/12.702184

hardware since some of the light is inevitably scattered toward these structures. The result is an additional uncertainty in the operating wavelength of the VBG-locked laser diode stacks that compounds the manufacturing tolerances of the VBG elements.

Fortunately, these issues can be relative easily resolved when VBG elements with transverse chirp are employed for wavelength tuning (TC VBG). These elements have a Bragg period that varies smoothly as a function of a position across their clear aperture (Fig. 1). As a result, when such an element is aligned to lock a laser diode and then translated along the direction of the chirp, the output wavelength of a laser diode is tuned continuously. Since volume manufacturing costs of such elements are very similar to those of "standard" VBG elements with constant period the use of such elements allows for a simple and cost-effective way of precise "dialing" of a required output wavelength, which is ideal for an application requiring as high a wavelength precision as such demanded by pumping of alkali vapor media.

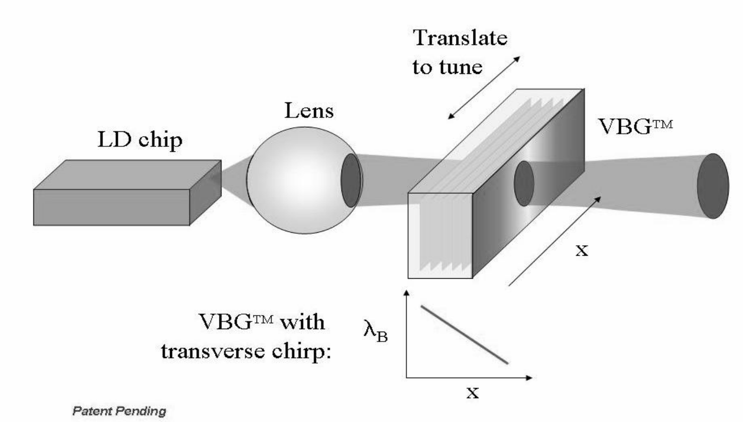

Fig. 1 VBG diagram with transverse chirp.

The described method works very well when a single emitter or a linear array of laser diode emitters is used as a pump source. However, when a stack of laser diode bars is used for pumping, a single TC VBG element is of little help for the task since it will produce different output wavelengths between the different bars in the stack. What is required, is simultaneous and identical wavelength tuning of all the bars in the stack. In order to achieve this, we developed a special kind of TC VBG elements – VBG with Newport Corporation's patent pending periodic transverse chirp (PTC VBG). Such an element has multiple sections with identical chirp formed across its clear aperture (Fig. 2). The period of the structure is the same as the period of the bars in the stack. Due to such construction each of the bars in the stack is coupled to a section of the PTC VBG with the same Bragg period that can be adjusted simultaneously for all the bars in the stack.

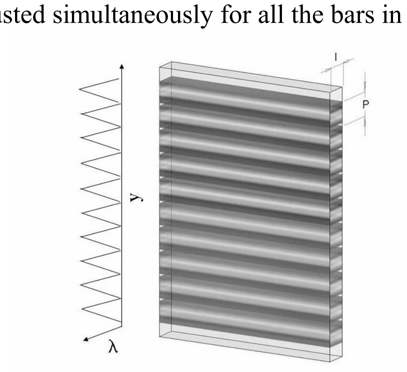

Fig. 2 PTC VBG configuration

2. FABRICATION OF PTC VBG

When fabricating a PTC VBG element there are several important considerations that need to be taken into account. First of all, the period of the PTC VBG needs to match that of the laser diode stack. Any deviation in the position of a bar in the stack or error in the PTC VBG period will result in a slightly different output wavelength of that bar and, ultimately, broadening of the output spectrum of the stack. Second consideration is the rate of the chirp. For this application the stack is equipped with fast axis collimating (FAC) lenses that produce a beam of finite size collimated in one direction from every bar in the stack. These beams of finite size cover a certain area on the surface of the PTC VBG and, due to the continuously varying period of the latter, that creates feedback into the laser diode bar within a bandwidth of light $\Delta\lambda_{chirp}$ that is proportionate to the size of the beam d and the rate of the chirp c:

$\Delta\lambda_{chirp} = dc$.

Since the stack is manufactured with a certain bandwidth in mind, the amount of line broadening due to chirp should not exceed that value. Moreover, the thickness l of the PTC VBG should be selected such that it's natural bandwidth

$\Delta\lambda = \lambda^2/2nl$,

where n is the bulk refractive index of the material, mostly determines the line width of the stack output. In other words, we would want $\Delta\lambda_{chirp} < \Delta\lambda$. Using these criteria we have determined the specifications for the PTC VBG required for the application (see Table 1).

Table 1. Design parameters of the PTC VBG element used in the experiments.

Parameter	Design value	Units
Center wavelength	780	nm
Bandwidth	< 0.3	nm
VBG™ thickness	1.5 - 2	mm
Reflectivity	20 - 30	%
Transverse chirp rate	0.3	nm/mm
Chirp period	1.81	mm
Aperture	20x14	mm

Figure 3 shows the spectral response function of the recorded PTC VBG element measured in end positions of a single chirp period. Note that in testing the element the incident beam had 1 mm Gaussian diameter and, therefore, the width of the spectral response function is dominated by the chirp of the grating.

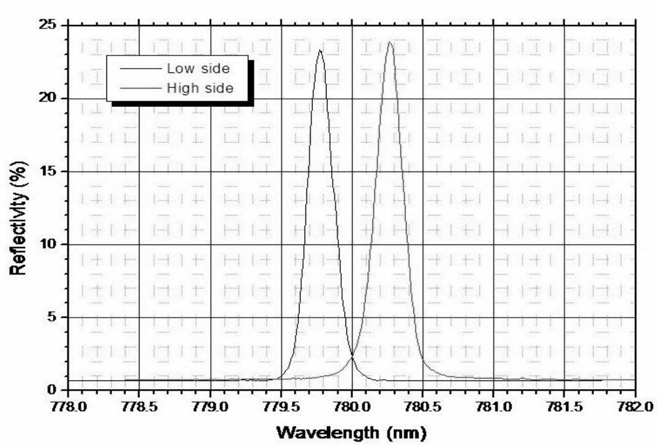

Fig. 3 Spectral response of grating shown at high (780.25nm) and low (779.80nm) centroid chirp limits.

3. STACK CONFIGURATION

A custom twenty bar vertical stack was assembled with two ten bar diode arrays separated by an electrically conductive spacer. The purpose of the spacer was to allow an open aperture to be inserted between the optical outputs of the stacks for the final output beam propagation generated by the gain medium. The spacer was constructed with a terminal contact so that either the bottom ten bar array or top ten bar array could be operated electrically isolated from the other. In order to keep the stack pitch relative to the PTC VBG period physical offset error minimized, the standard pitch of 1.80mm was increased to 1.81mm and 0.025mm thick conductive spacers were located strategically throughout the stack. Using this technique, it was possible to keep the nominal location error variation below ten microns as shown in Fig. 4. Individual micro-lenses were then actively aligned and secured to individual diode bars to minimize the fast axis divergence. Two discrete PTC VBG elements were loaded in a separate mechanical frame, secured with clamps, and then attached to the stack manifolds. The frame allowed micro-adjustment of the individual PTC VBG elements by the use of two differential screws and pusher rods against opposing spring plungers. All other degrees of freedom were passively aligned and restrained by the mechanical machined tolerances of the frame. See Fig. 5. Rotation of the micro-adjustment screw resulted in translating the respective PTC VBG along the chirp axis allowing for wavelength centroid tuning. Each rotation of the adjustment screw results in a 158 micron displacement across the chirp.

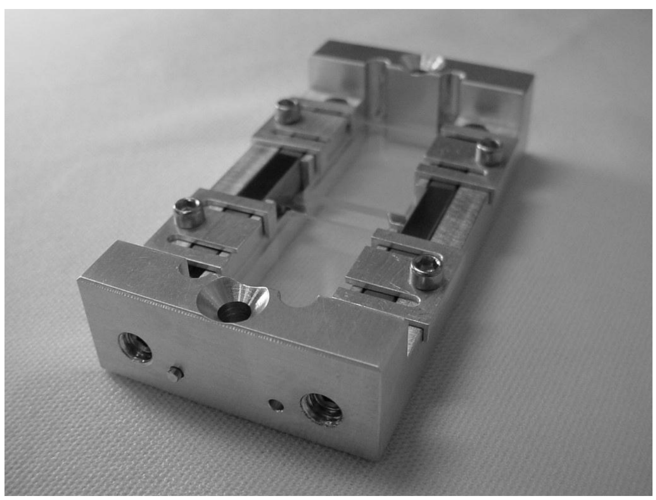

Fig 5. Mechanical frame shown with two separate PTC VBG elements. Four clamps shown are used to secure the location once adjustment with differential screw is performed.

4. STACK OPTICAL ALIGNMENT AND PERFORMANCE.

The bottom half of the stack (bars 1-10) was actively aligned to the PTC VBG while monitoring the combined spectral shape and centroid of the ten bars. Fig. 6 shows the tunable range of the ten bars as the PTC VBG was vertically translated across the usable chirp. The bandwidth stayed under 0.35nm for the range of 1.5mm.

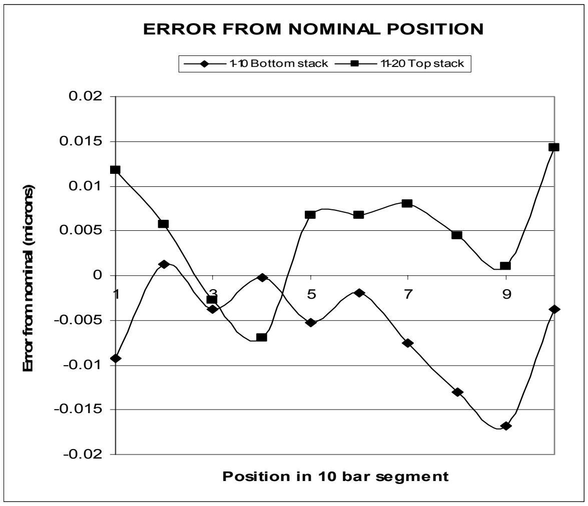

Fig. 4 Location error bar to PTC VBG pitch

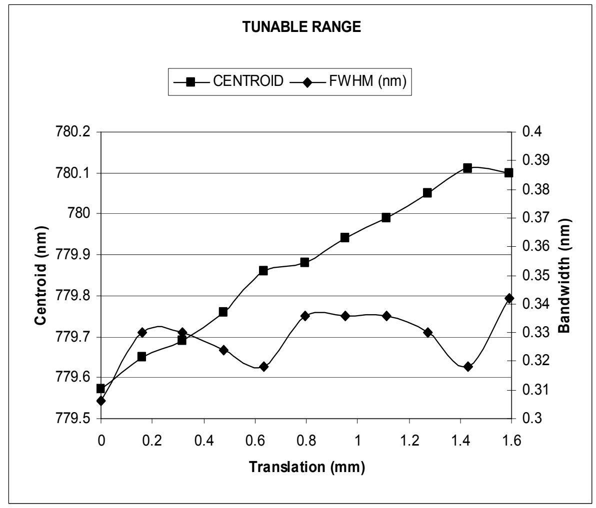

Fig. 6. Tunable range and FWHM bandwidth

Once aligned in the desired location, the PTC VBG was secured with the two clamps. Next, with the entire stack activated, the top PC-VBG was aligned while minimizing the output bandwidth output of the entire twenty bars.

5. CONCLUSION

It has been demonstrated that high power stacks utilizing PTC VBG technology can create narrow tunable bandwidths under 0.35 nm FWHM while offering mechanical centroid tuning of +/- 0.25nm. Fig. 7 shows the output performance of the raw lensed stack running at 100% duty cycle without the aligned PTC VBG optics. At 18C, 70A and 1083W of CW power was realized with a FWHM bandwidth of 2.32nm for the entire twenty bars. Fig. 8 shows the optical performance of the entire stack after alignment of the two PTC VBG optics. As shown in Fig 8, at 18C and 70A, average power of 212W at 20% duty cycle an output centroid of 780.08nm was achieved with a FWHM bandwidth of less than 0.33nm encapsulating greater than 70% of the total output power.

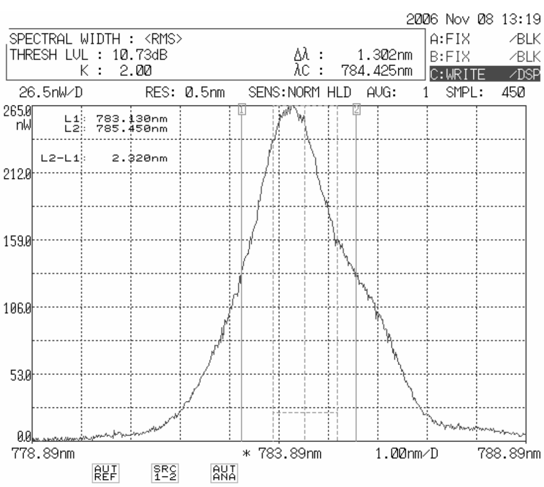

Fig. 7 Stack output without aligned PTC VBG.

(1.0 nm per division / full range 10 nm)

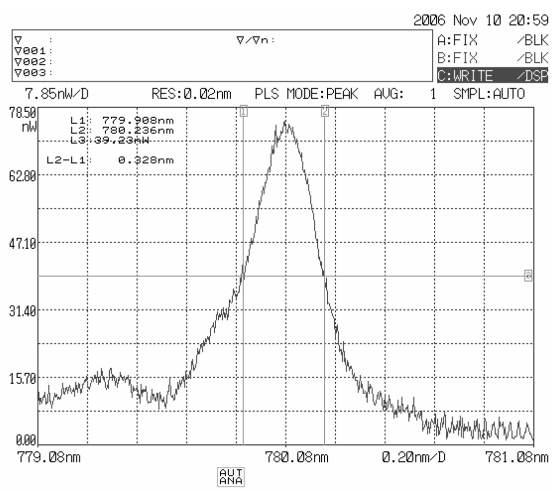

Fig. 8 Stack output with aligned PTC VBG

(0.2nm per division / full range 2nm)

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