

# Performance enhancement of the high-power laser diodes and arrays by use of the volume Bragg grating™ technology

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**Abstract:** Volume Bragg grating™ (VBG™) technology has been shown to improve spectral characteristics of the high-power laser diodes and arrays. We review the recent advances in VBG technology that lead to better spectral performance as well as improvements in spatial brightness of the high-power laser diode arrays. The VBG technology has been applied to manufacturing of high-power laser diode arrays suitable for spectral beam combining to achieve even higher spatial brightness. The approach involves fabrication of VBG™ elements with transverse chirp of the Bragg period. Wavelength tuning of the laser diode arrays and wavelength-shifted laser diode bar operation have been demonstrated, which will lead to manufacturing of spectrally combined high-brightness arrays.

**OCIS codes:** (140.2020) Diode lasers; (140.2010) Diode laser arrays; (050.7330) Volume holographic gratings.

## 1. Introduction

Over the past year the technology of the Volume Bragg Gratings™ (or VBGs™\*) has proven a simple, robust and efficient technique for improving the spectral properties of the broad-area high-power laser diodes and laser diode arrays. It achieves passive wavelength stabilization (drift ~ 0.01 nm/K) and line narrowing (typical line width ~ 0.2 nm FWHM) without changing the form factor of the packaged laser diodes and laser diode arrays [1, 2]. The increased spectral brightness and wavelength accuracy and stability against temperature are valuable features for a variety of applications, such as solid-state and alkali vapor laser pumping, spectroscopy, medical, gas sensing and others.

In this paper we describe the results of the recent experiments performed with the VBG™ technology that pave the way for further advances in its applications.

## 2. The effects of the VBG™ parameters on the performance of the high-power lasers

The general principle of laser wavelength stabilization by use of the VBG™ elements consists in positioning such element in front of a laser and, typically, after a fast axis collimating (FAC) lens so that the Bragg planes are perpendicular to the direction of propagation of the laser light and, therefore, reflect the light directly back into the laser cavity. The spectral selectivity of the VBG™ is determined by the number of the Bragg planes that the light traverses inside the glass. For the wavelength in the range 700 – 1000 nm and for the VBG™ element thickness in the range 0.5 – 2 mm it yields the bandwidth of 0.15 – 0.8 nm.

VBG™ elements produced at PD-LD Inc. are made in very stable inorganic photorefractive glasses. These glasses are physically and chemically very stable, hard and have very high optical damage threshold (approximately the same class as BK-7 glass) and temperature stability of the recorded Bragg gratings (tested to 200C). Thermal drift of the central wavelength of a VBG™ element is 0.01 nm/K.

The primary effect of the narrowband feedback from a VBG™ element into the laser cavity is the appearance of the new lasing peak at or near the wavelength of the peak reflectivity of the VBG™ element. When the feedback reaches sufficient strength the modes that are oscillating under the envelope of the VBG™ reflectivity curve consume all the laser gain and its emission spectrum collapses into a narrow line whose bandwidth is approximately equal to that of the VBG™ element. Thus the output spectrum of the laser becomes “locked” to the VBG™ element.

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\*) “VBG™” and “Volume Bragg grating™” are the trademarks for PD-LD, Inc.

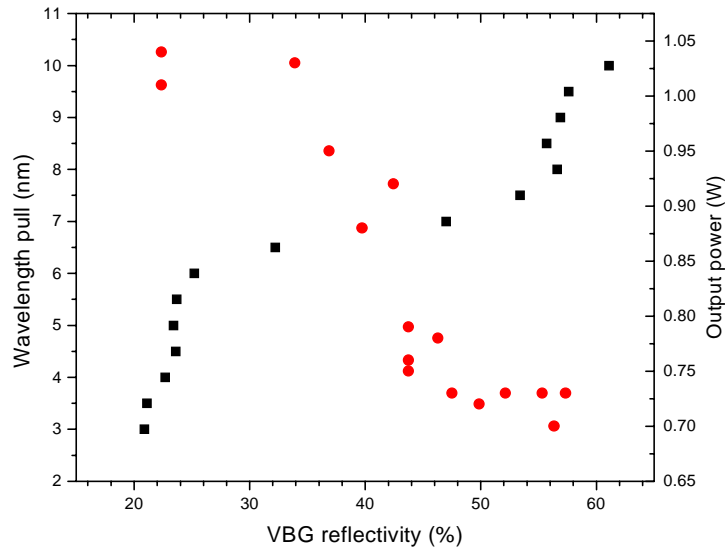


Fig. 1. The dependence of the wavelength pull exerted by a VBG<sup>TM</sup> element on the maximum VBG<sup>TM</sup> reflectivity (squares) and the dependence of the laser output optical power on VBG<sup>TM</sup> reflectivity (circles). The laser used in the test was operating at 781 nm and had 1x100 μm emitting aperture. The reflectivity of the front facet was approximately 1%. Only FAC collimating lens was used, the slow axis of the laser was not collimated.

The amount of the feedback the laser receives from the VBG<sup>TM</sup> element has a strong influence on the wavelength “pull” that the VBG<sup>TM</sup> produces on the laser and also on the total output power. Fig. 1 shows the dependence of both on the maximum reflectivity of the VBG<sup>TM</sup> element. Note that the maximum VBG<sup>TM</sup> reflectivity is only realized when the incident light is well-collimated on both axes, which is not the case in the conditions of the experiment being described (only FAC lens was used, the same one in all cases). As is evident from the results of the test, the VBG<sup>TM</sup> reflectivity has a pronounced effect on both the wavelength pull and the output power, which is also different for different lasers. For the laser tested in the experiment the optimum reflectivity would be in 25 – 30% range for typical operating conditions. Note that the criterion for the laser to be locked was the side-mode suppression ratio of > 30dB.

The secondary possible effect of the VBG<sup>TM</sup> feedback is its influence on the slow axis divergence of the broad-

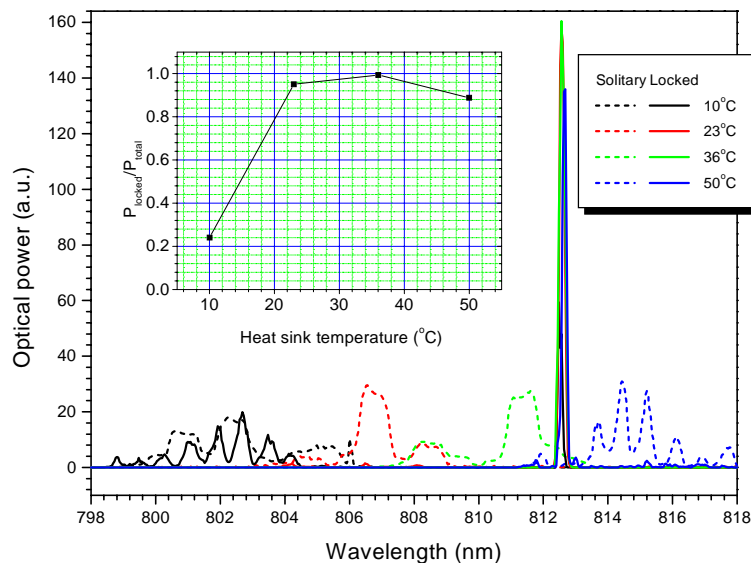


Fig. 2. (Main) Spectra of a laser diode bar locked by a VBG<sup>TM</sup> at different temperatures. (Inset) Ratio of the optical power contained in a 0.8 nm (full width) window near the main peak to the total optical power produced by the bar as a function of the temperature of the heat sink. VBG<sup>TM</sup> maximum reflectivity was 30%. Only FAC lens was used.

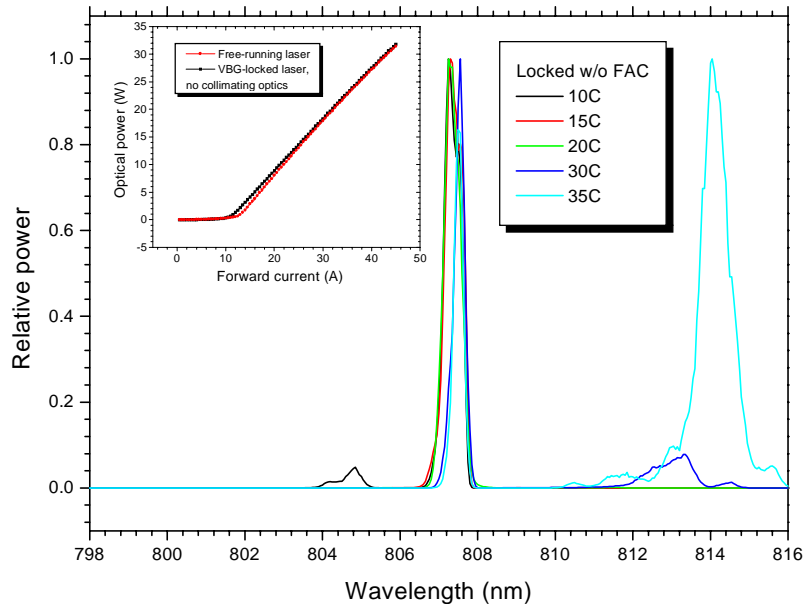


Fig. 3. (Main) Spectra of a laser diode bar locked with a VBG element without using any collimating optics. The temperature of the heat sink was varied and all the spectra were normalized. Laser diode bar had 4% reflectivity on the front facet. Maximum reflectivity of the VBG element was 40%. (Inset) Optical power of the laser diode bar when free-running and locked by the VBG.

area laser diodes. As reported previously [2], when the feedback from the VBG<sup>TM</sup> is sufficiently strong and its alignment is properly optimized, a narrow divergence peak appears in the far field of the laser emission. This effect was observed on single-emitter laser diodes and on laser diode bars as well. At the same time, not all the lasers are equally susceptible to such an effect. However, it is clear that reducing the reflectivity of the laser front facet increases such susceptibility in all lasers.

One of the practically important aspects of locking the laser wavelength by VBG<sup>TM</sup> elements is the simplification or, in some cases, even complete elimination of the temperature control on the pump laser diodes (e.g. those used in compact and energy-efficient solid-state lasers). When increase in the operating temperature range is desired, it is measured by the proportion of the power in the locked portion of the laser spectrum vs. the total output power of the laser. An example of such effect is shown in Fig. 2. It shows the proportion of the output power of a laser diode bar that is locked in a narrow wavelength range (0.8 nm) vs. the total output power of the diode bar integrated over 20 nm range. As is evident from this figure, the VBG<sup>TM</sup> locking of the laser diode bar extends the operating temperature range to about +/- 15 degrees C. The useful operating temperature range is a function of many variables, however. Two such most important variables, besides the structure of the laser itself, are the front facet reflectivity and the amount of the feedback from the VBG<sup>TM</sup>.

### 3. Other experimental results

As is evident from Fig. 2, relatively substantial amount of feedback is required to achieve wide range of stability of the wavelength characteristics of a laser diode. However, as we have found, it is not always necessary to have equally strong feedback in order to achieve the increase in spectral brightness. For example, it is possible to achieve spectrum narrowing without the use of any FAC lens. Figure 3 shows an example of the behavior of a laser diode bar when locked by a VBG<sup>TM</sup> element without use of any collimating optics. As seen in the figure, the spectrum narrowing and stabilization occurs even in this condition of extremely weak feedback. However, the temperature range where most of the power is concentrated in the locked portion of the spectrum is substantially smaller than when a FAC lens is used (in the two cases shown here, the reduction of the locking range was by approximately factor of 3). At the same time, the small amount of feedback from the VBG<sup>TM</sup> into the laser cavity achieves truly insignificant change in the output power of the laser (see inset of Fig. 3). Note also that essentially no optical alignment is required to achieve locking when VBG<sup>TM</sup> is used without collimating optics. This is expected since the divergence of the uncollimated laser diode beam is so high that certain portion of emitted light will always

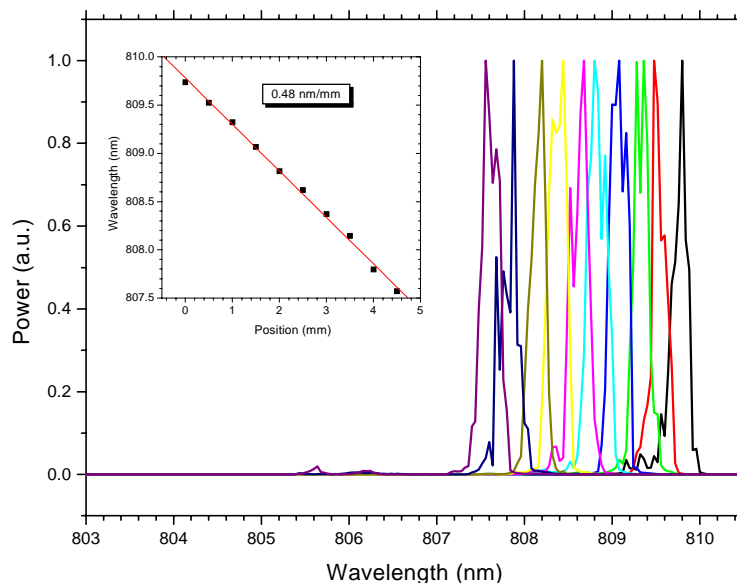


Fig. 4. (Main) Output spectra of different emitters in a laser diode bar that was achieved by use of a VBG<sup>TM</sup> element with transverse chirp. (Inset) The dependence of the wavelength of the individual emitters on their position in the laser bar array.

returns back into the laser cavity. The VBG<sup>TM</sup> element was initially placed in close proximity to the front of the laser chip, but it was quickly found that the sensitivity to this parameter was not critical, and separation of several hundred microns could be readily tolerated.

On the other hand, large amount of wavelength “pull” that can be achieved when higher level of the VBG<sup>TM</sup> feedback can be utilized, for example, to force different emitters in a linear array to operate at slightly different wavelength (Fig. 4). In this case a FAC lens was used and the VBG<sup>TM</sup> element that had continuously varying Bragg period along the dimension of the linear laser array (“transverse chirp”). The output of such wavelength-shifted laser diode bar can be spectrally combined for increased brightness using a diffraction grating or other wavelength multiplexing techniques.

#### 4. Summary

Wavelength stabilization and spectrum narrowing by use of VBG<sup>TM</sup> technology has been demonstrated on practically all types and varieties of high-power laser diodes by this time, including single emitter devices, laser diode bars and stacks. The positive outcome of the use of VBG<sup>TM</sup> technology is the increase in the operating temperature range and simultaneous increase in spectral brightness, which is particularly useful for laser diode stacks. The use of VBG<sup>TM</sup> elements with transverse chirp can be also used for efficient spectral combining of the output of laser diode bars and stacks.

These useful features of the VBG<sup>TM</sup> technology are making their way into practical systems, including the diode-pumped solid state lasers, free-space communications as well as medical and sensing applications requiring wavelength stability and/or high power in a narrow spectrum.

#### 5. References

1. B.L. Volodin et al., “Wavelength stabilization and spectrum narrowing of high-power multimode laser diodes and arrays by use of volume Bragg gratings,” *Optics Letters*, vol.29, p.1891-1893 (2004).
2. B.L. Volodin et al., “Efficient technology for wavelength stabilization and spectrum narrowing of high-power multimode laser diodes and arrays,” *Proceeding of the Advanced Solid State Photonics meeting*, (2004).