Efficient technology for wavelength stabilization and spectrum narrowing of high-power multimode laser diodes and arrays

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Abstract: We present a technology for achieving a significant line narrowing (by approximately an order of magnitude) and stabilization of the emission wavelength of multimode high-power laser diodes and arrays.

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1. Introduction

High-power laser diodes (HPLD, output power > 1 W) and diode arrays (> 20 W) have established themselves as an enabling technology for a variety of applications, such as solid-state and other lasers pumping, spectroscopy, medical, gas sensing and others. In a large number of cases HPLDs are used to excite a medium with narrow absorption lines. Some examples are pumping of the rare-earth-doped crystals, metal vapors and gases. In addition, Raman spectroscopy also requires a narrow-line, high-power source to achieve the required resolution and signal-to-noise ratio. A typical free-running HPLD has spectral line width of about 2-3 nm and drifts ~ 0.3 nm per K, which makes it rather ill-suited for the above applications (e.g. metal vapor absorption lines are typically < 0.1 nm wide).

The range of available solutions for laser diode line narrowing and stabilization has been quite limited. Perhaps the only technology currently deployed in the field is the fiber Bragg grating (FBG) stabilized single-mode laser diodes used for pumping the erbium-doped fiber amplifiers (EDFAs) used in long-haul telecommunication networks [1]. However, FBG technology is not applicable to the diode arrays and, besides, has been demonstrated only for single transverse mode laser diodes. In the case of multi-mode HPLDs and arrays the options have been limited so far to the use of diffraction gratings [2], resulting in rather bulky and costly devices that are only viable for high-end applications unconstrained by space.

The technology described in this paper presents a very simple and robust way to stabilize the emission wavelength and simultaneously narrow the line width of single-emitter HPLDs, laser diode bars and even stacks. This technology, based on the volume Bragg gratings (VBG™) manufactured in the bulk of inorganic photorefractive glasses, 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.

2. VBG™ laser stabilization technology

The principle of laser wavelength stabilization by use of an external feedback is well known [1, 2]. Generally, it comprises a wavelength-selective device positioned in the optical path of the laser emission that feeds a narrow portion of the laser emission spectrum back into the cavity. Although the general behavior of a laser diode under such feedback conditions is going to be rather similar no matter what wavelength-selective device is used, the practical implications can differ enormously.

The approach reported in this paper utilizes VBG™ elements – Bragg gratings recorded in the bulk of photosensitive glasses. In this application a VBG™ element is positioned in front of a laser and 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 (Fig. 1). The spectral selectivity of the VBG™ is determined by the number of the Bragg planes that the light traverses inside the glass:

$$\frac{\Delta\lambda}{\lambda} = \frac{\lambda}{2nd} = \frac{\Lambda}{d} = \frac{1}{N},$$

where λ is the Bragg wavelength, $\Delta\lambda$ is the filter bandwidth, d is the thickness of the VBG™, n is the bulk refractive index, Λ is the period of the grating, and N is the number of grating planes that fit in the thickness of the material. Since VBG™ filters have typical thickness ranging from approximately 0.5 mm to 10 mm this results in the extremely narrow bandwidth of the VBG™ filters (typically from 0.05 nm to 0.5 nm).

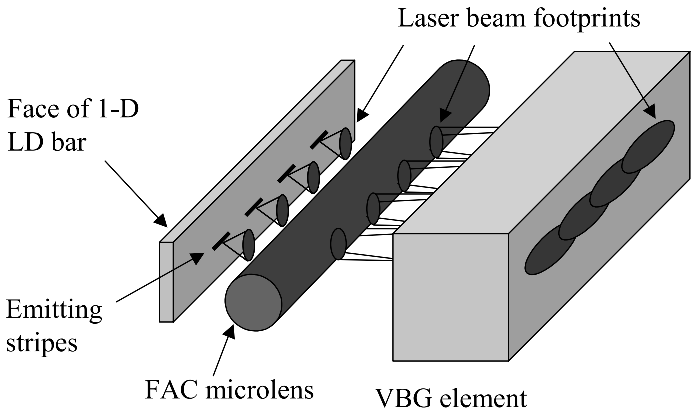

Fig. 1. Schematic of a laser diode bar wavelength stabilization by use of a VBG™ element. The laser output is collimated on the fast axis only, the VBG™ element is positioned after the lens and reflects small portion of light directly back into the laser cavity.

In order to achieve HPLD line narrowing on the order of 0.2 nm or less, the VBG™ element needs to be only 0.5 mm to 1 mm thick, with its clear aperture approximately equal to that of the collimating lens (typically ~ 1mm). This results in a very compact form factor, since a VBG™ element that small can easily be attached to the HPLD heat sink together with the FAC lens. Furthermore, the VBG™ is fabricated on a wafer level and later the wafer is diced into elements of the appropriate size. It is easy to see, therefore, that one VBG™ element can simultaneously lock the entire 1D or 2D array of HPLDs.

It is important to mention that VBG™ elements produced at PD-LD Inc. are made in very stable inorganic photorefractive glasses. Photosensitive glasses of the same class have been described in the literature in the past [3, 4]. 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.

3. Experimental results

We have tested a range of multi-mode single-emitter laser diodes and laser diode bars from a variety of the

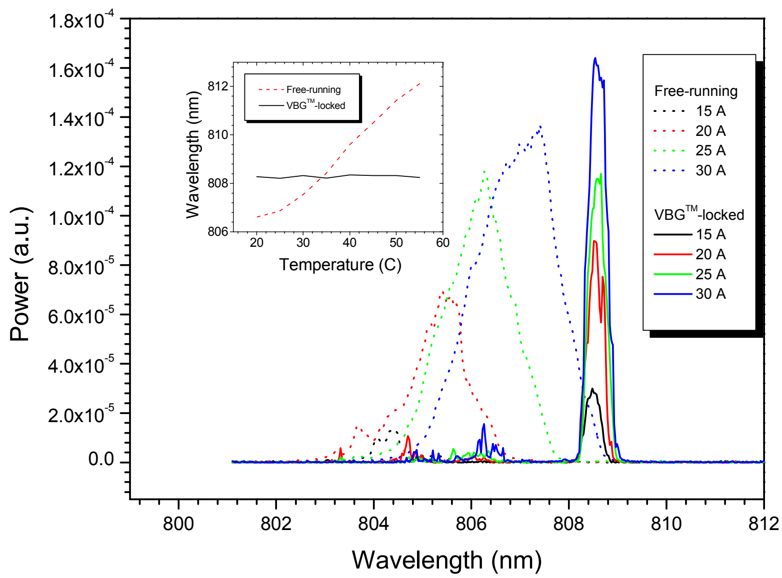

Fig. 2. (Main) Comparison of the output spectrum of a free-running and VBG™-locked diode bar at different drive currents. (Inset) Comparison of temperature drift of the central wavelength for a free-running and VBG™-locked lasers.

commercial suppliers. The laser diodes had emitting area ranging from 100 um to 500 um, output power ranging from 1 W to 5 W for single emitters and 20 W to 40 W for diode bars, with bar fill factor ranging from 0.2 to 0.5. The results have been rather similar in all cases and the most typical ones are shown in this paper.

The intrinsic reflectivity of the locking VBG™ element affects the amount of wavelength "pull" and generally increases with the increased reflectivity of the VBG™. However, it was generally observed that increase of the intrinsic VBG™ reflectivity beyond certain point did not lead to any further improvement in the amount of wavelength pull. The value of such saturation reflectivity appears to depend on the anti-reflection (AR) coating applied to the front facet of the HPLD – the lower the reflectivity of the AR coating, the lower the saturation reflectivity of the VBG™. For commercial laser diodes and bars with front facet reflectivity on the order of 10% we have observed the wavelength pull on the order of 3 to 4 nm with intrinsic VBG™ reflectivity of 30% to 40%. The amount of light fed back into the laser cavity is significantly less due to the fact that the laser output is not collimated on the slow axis (~ 1%).

A typical result of locking a laser diode bar with a VBG™ element is shown in Fig. 2. It clearly shows significant line narrowing and output wavelength stabilization against both the drive current and the temperature of

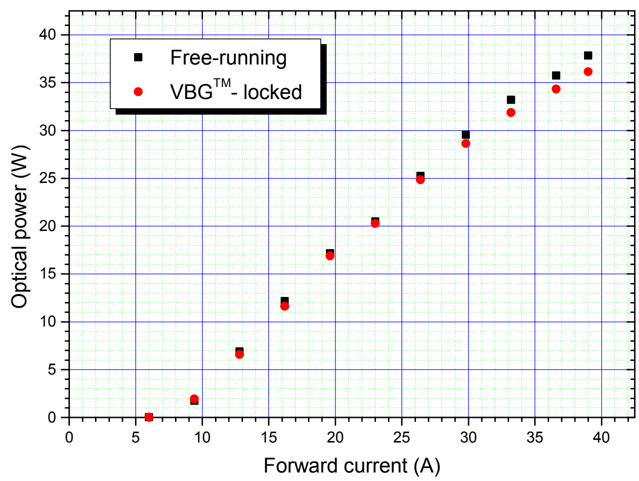

Fig. 3. Comparison of the power output of a 40W bar when free-running and VBG™-locked.

the heatsink. The output power difference between a free-running 40 W bar and the same bar locked with a single VBG™ element is shown in Fig. 3. It is very evident that the effect of the VBG™ element on the output power is rather negligible.

4. Summary

HPLD passive wavelength stabilization with VBG™ technology achieves line narrowing by factor of 8 and wavelength drift reduction by factor of 30 without change in form factor of a packaged laser or an array of lasers. The simplicity of the VBG™ approach makes it attractive and commercially viable.

The efficiency and robustness of this new technology has a potential of enabling new and wider uses of HPLDs via: a) simultaneous locking of multiple multi-mode laser diodes in a bar or a stack with a single VBG™ element; b) increasing the manufacturing yields of high power laser diodes due to wavelength pulling by the VBG™; c) greatly relaxing temperature control requirements; d) increasing pumping efficiency and decreasing the absorption length of the pump light in the DPSS and metal vapor lasers.

Improved emission characteristics of VBG™ locked diodes will lead to new applications of high power lasers (e.g. DPSS lasers based on new host materials), as well as new medical and sensing applications requiring wavelength stability and/or high power in a narrow spectrum (e.g. spin-exchange optical pumping for hyperpolarizing the noble gases for use in lung MRI diagnostics).

5. References

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