Wavelength stabilization and spectrum narrowing of high-power multimode laser diodes and arrays by use of volume Bragg gratings

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Spectral line narrowing (by a factor of 8) and stabilization of the emission wavelength (by a factor of 30) of multimode high-power laser diodes and arrays is demonstrated by use of volume Bragg gratings fabricated in high-stability inorganic photorefractive glasses. Applications include stabilization of pump laser diodes and arrays for solid-state lasers and metal-vapor lasers, spin hyperpolarization of noble gases used in medical imaging, and others. © 2004 Optical Society of America

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Broad-area high-power laser diodes (HPLDs) and laser diode arrays are an enabling technology for a variety of applications, such as pumping of solid-state lasers, medical treatment, Raman spectroscopy, and military applications. At the same time, there are clearly certain deficiencies in their performance that have become critical for many demanding applications: Their spectral linewidth is too broad (approximately 2–4 nm), the wavelength drifts with temperature (by approximately 0.3 nm/K) and changes with current and age, and the beam quality is poor.

A number of approaches have been tried to circumvent these problems, such as use of fiber Bragg gratings (applicable for single-transverse-mode individual laser diodes only[1–3]), diffraction gratings,[4–6] and metal-vapor cells[7] for broad-area HPLDs and arrays. Both diffraction gratings and metal-vapor cells, however, result in bulky and costly devices that are viable for only benchtop research installations or high-end applications unconstrained by space.

In comparison, the technology described in this Letter presents a simple and robust technique for stabilizing the emission wavelength and simultaneously narrowing the linewidth of single-emitter HPLDs, laser diode bars, and even stacks. This technology achieves passive optical wavelength stabilization (drift of ~0.01 nm/K) and line narrowing (typical linewidth of ~0.2–0.4 nm FWHM) without changing the form factor of the packaged laser diodes and laser diode arrays.

The principle of laser wavelength stabilization by use of external feedback typically comprises a wavelength-selective device positioned in the optical path of the laser beam that feeds a narrow portion of the laser emission spectrum back into the laser cavity.[8] What differentiates between different techniques is the convenience, robustness, compactness, and manufacturability of such components.

The approach reported in this Letter utilizes volume Bragg grating (VBG) elements recorded in the bulk of photosensitive glasses. These elements contain Bragg planes of varying index of refraction that penetrate the entire volume of the material. VBG structures are recorded in the material by light with holographic techniques or phase masks. The glass used in this experiment is an alumo-sodia-silicate material doped with silver and sensitized by cerium. Photochemical changes initiated in this material by light during the exposure process are completed in the thermal annealing step that is performed at temperatures exceeding the glass transition temperature of the material (T_g) and typically ranging from 500 to 600 °C. Photosensitive glasses of the same class have been described in the literature.[9,10] These glasses are physically and chemically stable and hard and have a high optical damage threshold (approximately of the same class as BK-7 glass) and temperature stability of the recorded Bragg gratings (tested to 200 °C). The material used for the experiments described in this Letter is produced by PD-LD, Inc., for its internal use. The glass is produced by use of conventional small-batch glass-melting techniques; i.e., raw materials are batched, charged in a crucible, melted, cast out in the molten state, and annealed.

In contrast with surface diffraction gratings, reflective VBG structures are not dispersive elements. Rather they operate as single-wavelength mirrors [Fig. 1(a)]. The spectral selectivity of a reflective VBG element is determined by the number of Bragg planes that light traverses inside the glass[11]:

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

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.

To achieve significant HPLD line narrowing, the VBG element needs to be only 0.5–1 mm thick, with its clear aperture approximately equal to that of the collimating lens (typically ~1 mm). Such a compact VBG element can easily be attached to the HPLD heat sink together with the fast-axis-collimating (FAC)

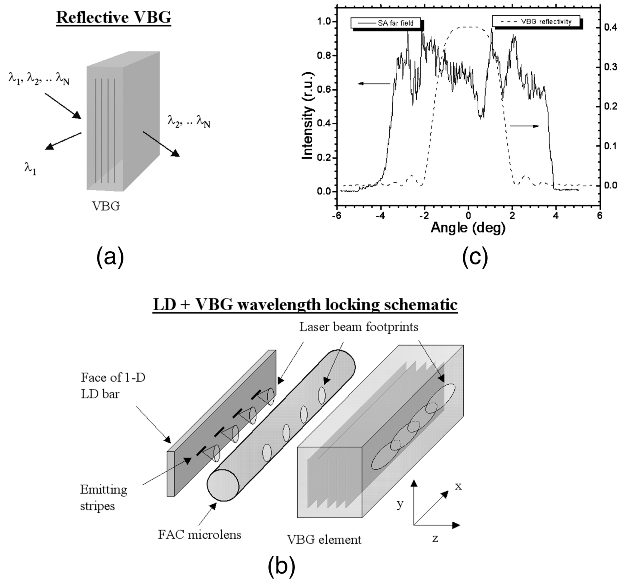

Fig. 1. (a) Illustration of the operation of a reflective VBG element. When a broadband light is incident on a VBG, only a narrow portion of the spectrum (single wavelength) is reflected by it, while all wavelengths outside the VBG reflectivity band are passing through unaffected. (b) Schematic of a laser diode (LD) bar wavelength stabilization by use of a VBG element. The laser output is typically collimated on the fast axis only; the VBG element is positioned after the lens and reflects a small portion of the emitted light directly back into the laser cavity. (c) Comparison of the slow axis (SA) divergence of a typical broad-area laser diode with the dependence of the reflectivity of a VBG (0.8 mm thick) on the incident angle for a given wavelength. Narrow angular acceptance of a VBG strongly reduces the total amount of monochromatic uncollimated light reflected by it. r.u., relative units.

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 one- or two-dimensional array of HPLDs.

Wavelength-locking tests were conducted on a number of single-emitter laser diodes and laser diode bars from a variety of commercial suppliers [emitting aperture of 100–500 μm, power of 1–5 W (single emitters) and 20–60 W (bars), fill factor of 0.2–0.5 for bars]. Spectrum narrowing and wavelength stabilization have been observed in all cases so far. In this Letter we restrict ourselves to discussion of the most representative results.

To lock a HPLD or an array, a VBG element is positioned after a FAC lens [Fig. 1(b)]. Typically, only the fast axis was collimated [FAC effective focal length (EFL) of ~200 μm]. VBG elements had different maximum reflectivity (i.e., measured with light well collimated on both axes) ranging from 20% to 60%. Note that, because of the finite acceptance angle of the VBG, its actual reflectivity is significantly smaller when the slow axis of the laser is not collimated[11] [Fig. 1(c)]. An even smaller portion of the reflected light enters back into the laser cavity. It was not possible to measure directly how much light was directed back into the diode laser cavity at the time of the experiment.

The VBG element is aligned by rotation around two axes, *x* and *y*, shown in Fig. 1(b). The alignment tolerances depend on the EFL of the FAC lens and the quality of collimation—the longer the EFL and the better the collimation, the tighter the alignment tolerances. For the lenses used the alignment tolerance on the *x*-axis rotation was approximately ±4 mrad.

Figure 2 shows the effects of the FAC lens and the VBG on the spectrum of a single-emitter laser diode (main figure) and a laser diode bar (inset). The same laser diode (or bar) was used in all experiments. For spectral measurements light was collected by a multimode optical fiber (100-μm core, 0.22 N.A.) positioned directly in the beam path (for single emitters) or attached to a port of an integrating sphere (for bars) and then fed into an optical spectrum analyzer. The results show that the FAC lens alone creates destabilizing feedback into the laser cavity (due to imperfect antireflection coating on the lens surfaces), the VBG overpowers the FAC feedback and forces narrowband emission on its peak wavelength. The side-mode suppression ratio is >45 dB for the single-emitter laser. Note that, although not clearly resolved, there are several longitudinal modes (mode spacing of ~0.05 nm) lasing under the VBG reflectivity envelope (FWHM 0.3 nm).

Figure 3 shows the output power of the same single-emitter laser in different cases. The FAC lens slightly reduces the laser threshold current and its slope efficiency (SE), which is consistent with the evidence of the lens feedback into the laser cavity, as seen in the spectrum in Fig. 2. The unaligned VBG element has little or no effect on the laser threshold but reduces the slope efficiency to 0.96 of that of the lensed

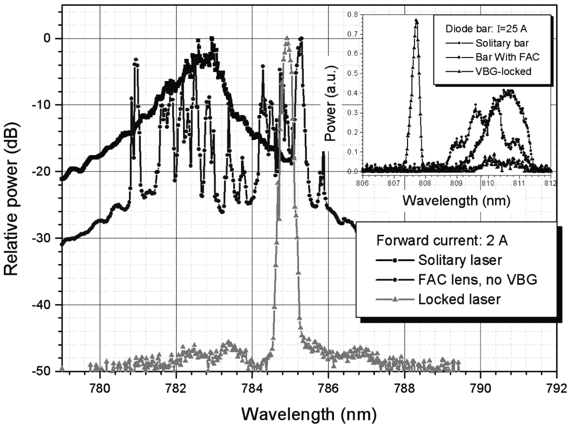

Fig. 2. Comparison of the output spectrum of a free-running and VBG-locked single-emitter laser. The laser diode parameters are 2-mm cavity length, 1 μm × 100 μm emitting aperture, and approximately 0.5% front facet reflectivity. The VBG parameters are approximately 30% maximum reflectivity and 0.84-mm thickness. Inset, comparison of the output spectrum of a free-running and VBG-locked laser diode bar. The laser bar parameters are 19 emitters, 1 μm × 150 μm emitting aperture for each emitter, and approximately 17% front facet reflectivity. The VBG parameters are approximately 60% maximum reflectivity and 0.9-mm thickness.

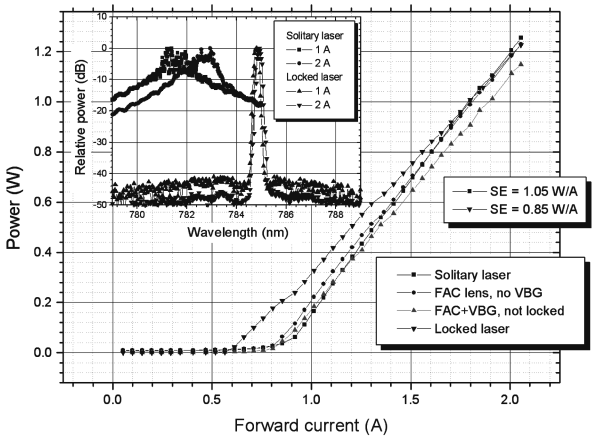

Fig. 3. Output power versus current for a single-emitter laser diode under different conditions. The laser diode and the VBG parameters are the same as in Fig. 2. Inset, emission spectra of the laser diode at different currents when free running and locked by the VBG.

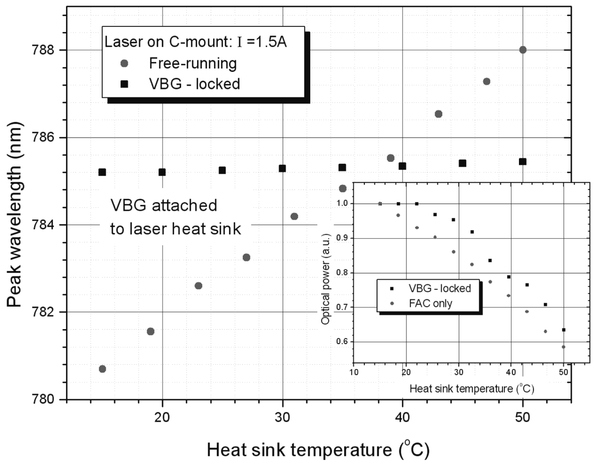

Fig. 4. Emission wavelength of a single-emitter laser diode as a function of the heat sink temperature when free running without a FAC lens (circles) and locked by a VBG (squares). The drive current is 1.5 A in both cases. The VBG element is attached to the laser heat sink during the experiment. Inset, output power of a locked (squares) and fast-axis-collimated (circles) laser diode as a function of its heat sink temperature.

laser (the VBG absolute transmission at off-peak wavelengths was 96% because of slight scattering loss). When aligned, however, the VBG reduces the threshold to 77% and the slope efficiency to 81% of the original values. The laser remained locked at all current values (see inset in Fig. 3). Note that, although certain threshold reduction and decrease in slope efficiency were always observed, the threshold current varied from ~0.65 to almost 1 and the slope efficiency varied from 0.7 to 0.9 of the original values. The lower front facet reflectivity of the laser and the higher VBG reflectivity led to the larger change in the output parameters of the laser.

Figure 4 shows the temperature dependence of the output wavelength of a single-emitter laser diode on a C mount when free running (without a FAC lens) and locked by a VBG. The same laser was used in both tests, and the temperature of the heat sink was allowed to stabilize before measurement of the wavelength. The wavelength drift was reduced by a factor of approximately 30 due to locking of the wavelength by the VBG element. The inset in Fig. 4 shows the change in laser output power with the temperature of the heat sink. The laser power follows the same general trend in both cases. The locked laser shows weak undulations of the output power that are probably due to the energy redistribution between the multiple oscillating modes of the locked laser.

In conclusion, we have demonstrated that narrowband feedback from a VBG simultaneously achieves spectrum narrowing by approximately an order of magnitude, wavelength accuracy improvement by pulling the laser emission wavelength to the required value (by ±3 nm typically, up to a ±10-nm maximum), and stabilization of the output wavelength against the drive current and temperature. It has also been observed that such feedback can significantly reduce the divergence of the slow axis. However, further studies of the conditions in which this effect occurs must be conducted. Although all the results presented here were obtained on broad-area lasers, it is expected that similar effects will be produced on single-transverse-mode devices; preliminary evidence confirms this expectation. Furthermore, we believe it will be possible to induce single-longitudinal-mode operation of the laser diodes with a properly designed VBG and laser chip.

Volume Bragg grating(s) and VBG are trademarks of PD-LD, Inc. B. Volodin's e-mail address is bvolodin@pd-ld.com.

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