Volume Holographic Grating Wavelength Stabilized Laser Diodes

Gregory J. Steckman, *Member, IEEE*, Wenhai Liu, René Platz, Dominic Schroeder, Christophe Moser, *Member, IEEE*, and Frank Havermeyer

(Invited Paper)

***Abstract*—Volume holographic gratings (VHGs) are the key components for producing laser diodes (LDs) with a temperature-stabilized wavelength and narrowed linewidth. We review the unique characteristics of these gratings that make them useful for this application as well as various alternative approaches of stabilizing LDs and their performance.**

***Index Terms*—Laser resonators, laser stability, laser thermal factors, volume holographic gratings (VHGs).**

I. Introduction

THE USE of volume holographic gratings (VHGs) to stabilize lasers dates back to the mid-1980s [1] with 1.55-μm-semiconductor lasers. Accuwave Corporation followed by applying optical feedback to visible and near infrared lasers from 670 to 840 nm [2]. However, at that time, lifetime issues with the $LiNbO_3$-based material prevented the commercial adoption of this technology. Advances in glass-based materials [3] have enabled the recent commercialization and broadened the application of this technology.

By providing wavelength-selective feedback into a laser diode (LD), a VHG can lock the lasing wavelength to that of the grating. This serves to lower the temperature dependence of the wavelength, narrow the spectrum, reduce the aging-related wavelength changes, and in the case of diode arrays, lock each emitter to the same wavelength, producing a much narrower combined spectrum than that in the unlocked arrays.

With the rapid developmental pace of high-power laser diode (HPLD) technology during the last decade, LD wall-plug efficiency now reaches 70% [4] with power levels greater than 100 W/bar. HPLDs are well suited for several applications including solid-state laser pumping, material processing, medicine, and instrumentation. The center wavelength of HPLDs and their spectral bandwidth are typically spread over a range of 3–5 nm. A narrower emission spectrum in the range of 0.1–0.5 nm and a smaller wavelength tolerance can be extremely beneficial for some applications (e.g., to increase pumping efficiency).

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G. J. Steckman, W. Liu, C. Moser, and F. Havermeyer are with Ondax, Inc., Monrovia, CA 91016 USA (e-mail: steckman@ondax.com; wliu@ondax.com; moser@ondax.com; havermeyer@ondax.com).

R. Platz and D. Schroder are with Jenoptik Laserdiode GmbH, Jena 07745, Germany (e-mail: rene.platz@jenoptik.com; dominic.schroeder@jenoptik.com).

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In Section II, we review the key attributes that make VHGs useful as wavelength-stabilizing components. Section III discusses various locking configurations that have been tested, and presents a new lens-free approach to wavelength locking.

II. VHGs

A VHG is a 3-D image of the interference pattern between two coherent optical fields [5]. It contains both the intensity and relative phase information from the two recording beams. The 3-D character gives the VHG unique features: high diffraction efficiency, simultaneous spatial and spectral selectivity, and multiplexing capability. Holographic recording can be performed with either thin or thick media. When the material in which the hologram is present is thick, Bragg selectivity occurs [6]. Kogelnik has analytically studied thick holograms with a coupled-wave analysis in [7]. In order to achieve high-diffraction efficiency, the material must additionally be low loss, and the grating must have a refractive index pattern, not an absorption pattern.

VHGs can have narrow spectral response (below 0.1 nm) and a small spatial acceptance angle (below 0.1°). A simple VHG formed by the interference of two collimated beams acts as a spectral filter with diffraction efficiency approaching 100%, narrow bandwidth, and precise central frequency. These features are important for several spectral filter applications such as laser line rejection, separating and combining beams of different wavelengths for spectral analysis, signal detection, power combining, wavelength-selective routing and switching, and improving LD emission characteristics by locking and stabilizing the wavelength.

In contrast to conventional thin diffraction gratings that angularly spread the spectral content of a light beam, thick gratings are not dispersive. Hence, they exhibit filter-like properties with more selective spectral and spatial features than other filtering technologies. Only the incident illumination satisfying the Bragg condition is efficiently diffracted (filtered), according to the relation

$$\lambda = 2n\Lambda\cos(\theta) \quad (1)$$

where λ is the wavelength, n is the bulk refractive index of the media containing the grating, Λ is the grating spacing (period), and θ is the angle of incidence (in media). Fig. 1 is an example of the spectral selectivity possible with a 1.5-mm-thick grating. Only when the Bragg condition is satisfied, does the diffraction efficiency reach its maximum. If the angle of incidence and the wavelength is changed according to (1), the grating can again

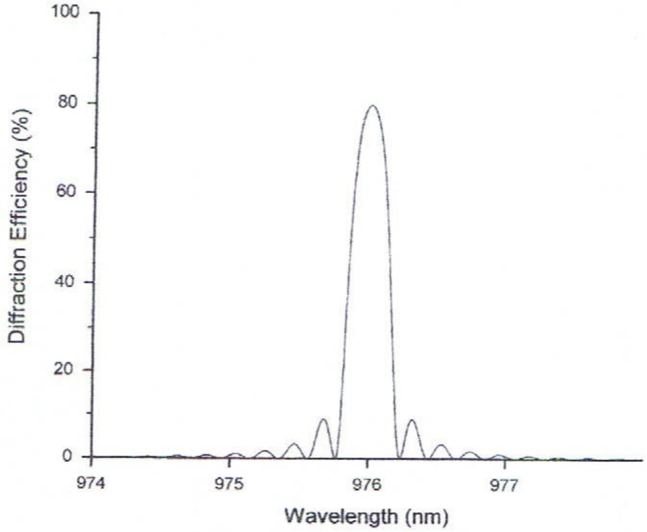

Fig. 1. Example of the wavelength selectivity of a VHG.

be Bragg-matched and the efficiency can be maximized. The width of the spectral response is primarily determined by the thickness of the grating. A thicker grating yields a narrower spectral response. The diffraction efficiency is controlled by the magnitude of the refractive index modulation depth established during fabrication of the grating. When used in a wavelength locking application, the diffracted beam is antiparallel to the incident beam, and (1) reduces to $\lambda = 2n\Lambda$.

Typical holographic photosensitive media include photorefractive crystals such as lithium niobate (LiNbO3), dichromated gelatin, photosensitive glasses, and photopolymers from companies such as DuPont, Aprilis, and InPhase. The major properties of a VHG material include photosensitivity, dynamic range (or maximum index modulation), manufacturability and available dimensions, optical quality, chemical and thermal stability, erasing and rewriting capability, shrinkage, and grating lifetime. Each holographic material has its own advantages and drawbacks in various respects, depending on the specific application requirements.

For laser applications, photosensitive glasses provide a wide operating range (350–2500 nm), a high-optical-damage threshold, and mechanical and thermal stability. Glass is also chemically inert and compatible with standard processes for cutting, polishing, and coating.

An important factor is the grating's long-term stability, which has long been a known problem for materials such as $LiNbO_3$ [8]–[10] and photopolymers [11]. Holographic gratings in photosensitive glass show outstanding stability at high temperatures. Fig. 2 shows the long-term stability of the Ondax photosensitive glass at a temperature of 150 °C for over 25 000 h. The refractive index modulation depth is shown in Fig. 2(a), demonstrating the consistent diffraction efficiency of the grating. The Bragg-matched wavelength is shown in Fig. 2(b), which is an indirect measure of the bulk refractive index by using (1), if the spacing of the grating is assumed to be fixed. Neither data indicate any change in the grating's performance at these temperatures.

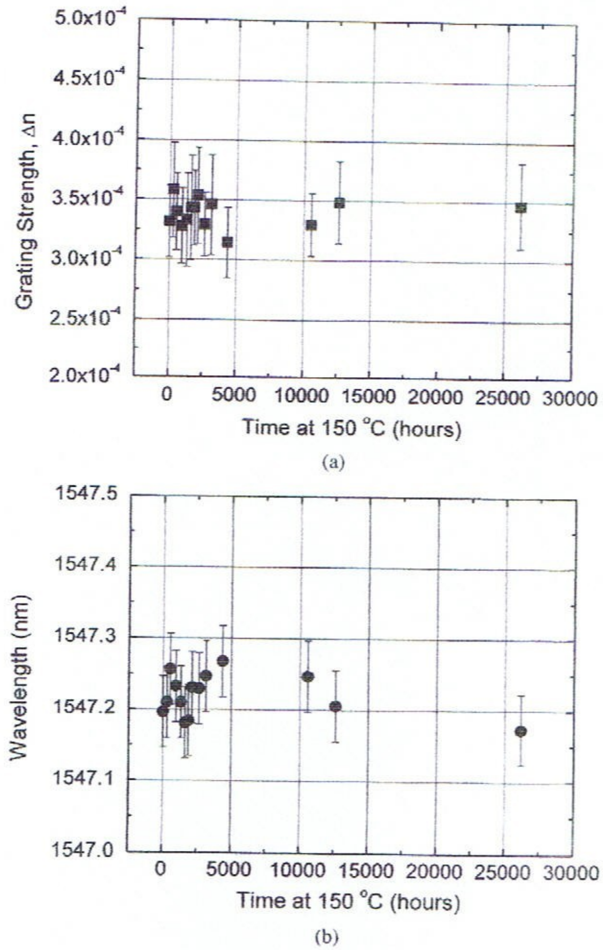

Fig. 2. High temperature aging of VHGs for over 25 000 h shows no sign of change in (a) grating strength or (b) wavelength.

III. Stabilized LDs

One of the commonly used methods for narrowing the spectra of LDs is the external-cavity technique, which uses an additional optical element to feed part of the laser output back into the LD cavity. The effects of external optical feedback on the characteristics of LDs have been researched for decades [12]–[15]. It is well understood that the external feedback can cause line narrowing, noise suppression, coherence collapse, multistable conditions, and hysteresis, depending on the feedback intensity, phase, and time delay relative to the coherence length of the intrinsic diode cavity. With wavelength-selective external feedback such as that provided by a fiber Bragg grating (FBG) [16]–[18], a diffractive grating [19], [20], or a VHG [21], [22], it is possible to control the wavelength and spectrum of an LD.

Compared to FBGs and surface diffraction gratings, the VHG has several key advantages for wavelength stabilization. It enables compact packaging by placing the element directly at the output laser facet or behind the collimating lens, high-damage threshold (typically 170 MW/cm^2), and low-temperature sensitivity.

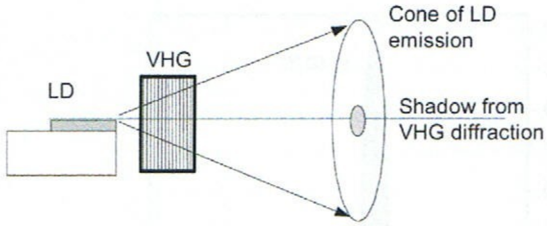

Fig. 3. Compact LD-VHG external cavity laser structure. The reflection-mode VHG diffracts a small Bragg-matched cone of the incident beam back into the LD facet.

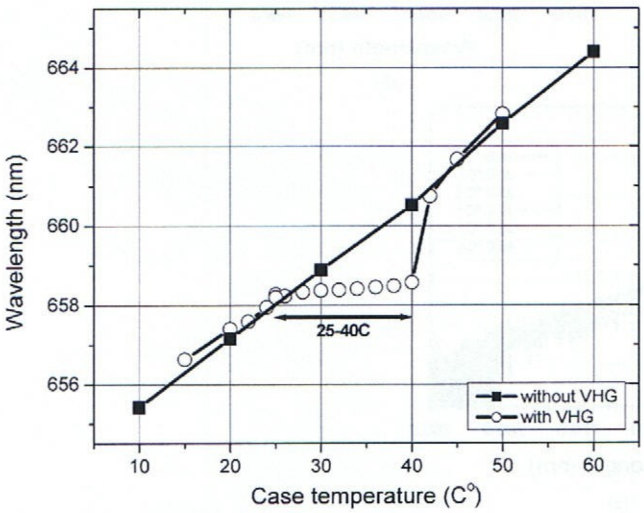

Fig. 4. Temperature-dependent wavelength shift of a stabilized and an unstabilized LD at 658 nm.

A. *Lens-Free Single Emitter*

Due to the sensitive angle and wavelength selectivity of a VHG, a reflection-mode VHG will Bragg-match, and strongly diffract a narrow range of wavelengths antiparallel to the incident beam. This makes it possible to implement a compact external cavity LD without additional optical components, such as collimation optics, as shown in Fig. 3. For a typical VHG with a thickness of 0.5 mm and Bragg wavelength of 700 nm, the full-width at half-maximum (FWHM) angle selectivity is about 5 °. The LD emits light with a large divergence angle dictated by the aperture of the LD's active area. For a typical beam divergence angle of 16 ° and 10 °, in the perpendicular and parallel directions, respectively, the maximum feedback from the VHG to the LD is about 10% or less.

Fig. 4 shows the experimental results for wavelength locking with a VHG attached to the output facet of a LD at 658 nm. In this design, the VHG is passively placed in close proximity to the LD facet. Without the VHG feedback, the output wavelength is very temperature dependent. When the LD case temperature is increased, the output wavelength of the laser increases by 0.18 nm/K. With the VHG feedback, the output wavelength is locked to the Bragg-matching wavelength of 658 nm for a temperature range of about 15 K. Within the locked range, the slope is 0.02 nm/K.

Due to the angle selectivity of the VHG, the feedback to the LD is limited. This limits the locked temperature range to less than 20 K due to the 0.2-nm/K-intrinsic shift of the LD's output wavelength. When the intrinsic output wavelength of the LD is too far from the VHG's Bragg wavelength, the feedback is insufficient to overcome the feedback of the internal cavity.

One method to increase the locked temperature range is to reduce the divergence angle of the LD by using a collimating lens in front of the LD facet. By collimating the beam, the feedback from the VHG is limited only by the diffraction efficiency and the optical coupling efficiency, as discussed later. This leads to a design with a larger package and more complicated active assembly procedure.

Another method to increase the temperature range over which locking occurs is to reduce the LD's internal cavity feedback by antireflection (AR) coating the output facet. Fig. 5 shows the results of VHG feedback on an AR-coated LD at 785 nm. Fig. 5(a) is a comparison of the *L–I* curves between the diodes with and without VHG feedback. Without external feedback, the diode shows a high-threshold current due to the small amount of feedback from the AR-coated facet. When a VHG is attached close to the LD's output facet, the threshold current is reduced to about 45 mA, and the output power significantly increases. This shows that the LD-VHG cavity is dominated by the VHG feedback. The output spectrum is narrowed, and the wavelength is locked to the Bragg wavelength of the VHG for a wide range of case temperatures, from 10 °C to 50 °C, as shown in Fig. 5(b). By comparison, without the VHG, the spectral width of the output is very broad, and the center wavelength varies more rapidly with temperature, as shown in Fig. 5(c).

The VHG-stabilized LDs that were tested have a single-longitudinal-mode output when locked at the Bragg wavelength. However, a VHG with a thickness of 0.5 mm has a FWHM bandwidth of about 0.5 nm. Within this bandwidth, mode hopping does occur when the temperature or current is changed. To investigate this mode hopping, we mounted the VHG onto a high-precision piezo-electric stage, and monitored the output wavelength as the VHG position was varied relative to the LD facet, while maintaining a constant temperature and drive current. Fig. 6(a) shows the results when operating within the locked regime. The wavelength varies periodically with a spacing of 330 nm (Δg), corresponding roughly to half the output wavelength. Within one period, the wavelength hops five steps with a mode distance of approximately 63 pm ($\Delta\lambda$), which corresponds to the external-cavity-mode spacing. A similar mode hopping is observed when the VHG is fixed but the case temperature is changed, as shown in Fig. 6(b).

B. *High-Power LD Bars*

A VHG can also be used to stabilize LD bars. A typical arrangement is shown in Fig. 7, where the VHG is placed after collimation optics that can be a fast-axis collimator (FAC), or both a FAC and a slow-axis collimator (SAC).

Bars with a standard facet coating at 808 nm were stabilized with VHGs having various diffraction efficiencies. The spectra and power were measured with an integrating sphere and spectrometer having a resolution of 0.11 nm. Fig. 8 shows the spectra of an unlocked and locked bar at 21 °C and 55.5 A drive

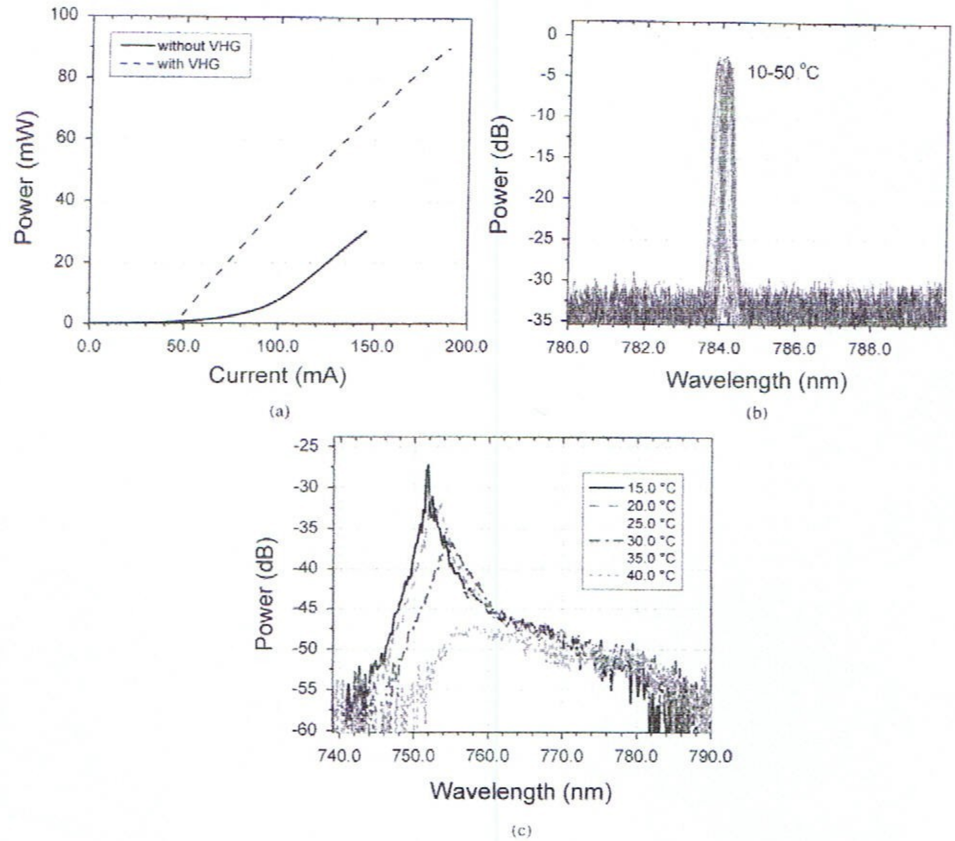

Fig. 5. (a) L–I curves of an AR-coated diode with and without the VHG feedback. (b) Spectra of the VHG-stabilized diode. (c) Spectra of the unstabilized diode.

current, with a 0.9-mm FAC lens. The locked bar had a VHG with a diffraction efficiency of 15%. The FWHM spectrum was narrowed from about 1.6 to 0.5 nm. The spectrum of the locked bar narrows primarily because the VHG forces all the emitters to lase at the same wavelength, as opposed to the free running bar in which each emitter may lase at a slightly different wavelength due to a number of factors such as manufacturing variations, temperature gradients, and so on.

Using a range of VHG diffraction efficiencies, the locking behavior was studied over a range of temperatures for a diode bar collimated only with an FAC and driven at 39.7 A. In Fig. 9, the center wavelength of the unlocked bar (labeled LDB + FAC) is shown to vary by approximately 0.3 nm/K. By comparison, within the locked range of 19 °C–29 °C the wavelength of the locked bar varies by only 0.01 nm/K. The center wavelength for the bar locked with the strongest VHG shows slightly less temperature dependence. Fig. 10 is a plot of the fraction of the total output power that is within ±0.5 nm of the peak for the three configurations tested. Within the locked range, over 70% of the power is contained within a 1-nm band. At the temperature extremes, some of the emitters fail to lock and lase at their natural wavelengths, causing the fraction of contained power to drop. Fig. 11 is a comparison of the L–I curve for the four cases tested. There is a little difference between the three different VHG efficiencies, all of them creating a laser that is slightly less efficient than the unlocked version. The locked laser bar had a slope efficiency that was about 10% lower than the unlocked bar. There was little or no change in the threshold current.

Much better performance can be achieved by using an FAC and an SAC to fully collimate the beam. This effectively increases the feedback by putting more of the laser power within the range of angles that are strongly Bragg-matched by the VHG. Fig. 12 shows the center wavelength over a range of temperatures for the same conditions as in Fig. 9, except with the addition of an SAC. Fig. 13 shows a plot of the fraction of the total output power that is within ±0.5 nm of the peak. Relative to the FAC-only configuration, the locking temperature range is extended, and the fractional power content is higher. Table I summarizes some of the key performance metrics for the FAC and FAC + SAC configurations.

A third configuration for bar locking was tested in which the VHG was shaped into an FAC lens (VHG FAC). This approach reduces the number of optical components and requires only one element to be aligned. Tests were performed with 976-nm LD bars using a spectrometer with a resolution of 0.22 nm. We found that poor collimation had no significant influence on the stabilized spectrum for both rotation and translation of the VHG. This indicates that the alignment sensitivity required for good collimation of the bar is higher than that required for good locking. If the lens is aligned for optimal collimation, then it is also aligned for optimal locking. The VHG FAC was always oriented with the planar side toward the laser.

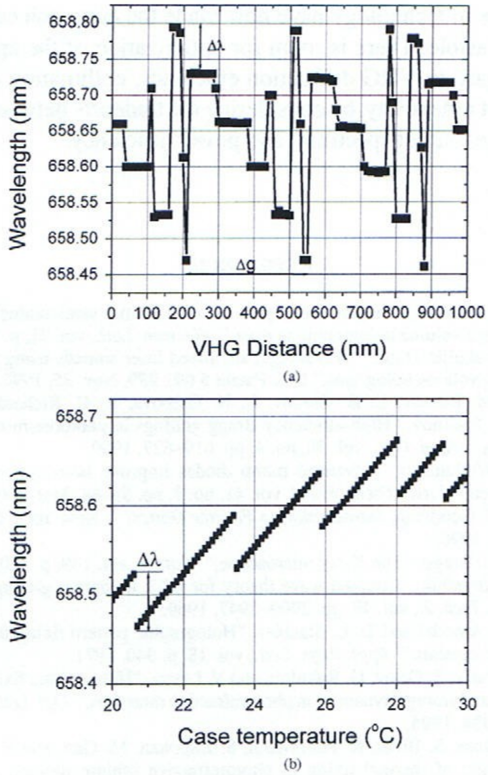

Fig. 6. Mode-hopping behavior of the VHG-stabilized LD. (a) When the VHG position is varied. (b) When the temperature is changed depending on the external cavity length.

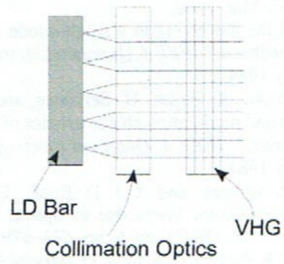

Fig. 7. Typical configuration used for stabilizing high-power LD bars with collimation optics.

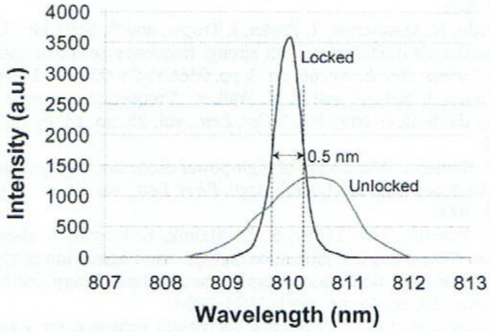

Fig. 8. Output spectra for locked and unlocked diode bars.

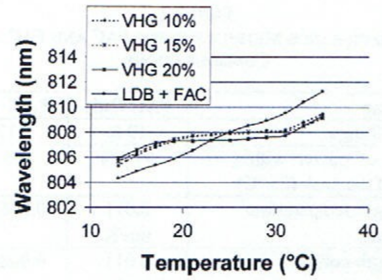

Fig. 9. Dependence of wavelength on temperature for locked and unlocked bars using a FAC.

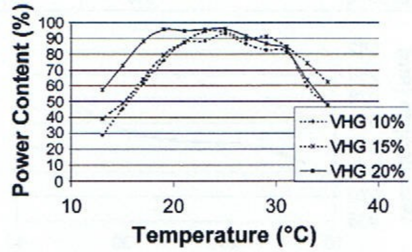

Fig. 10. For a diode bar using a FAC, the fraction of total output power contained within ±0.5 nm of the output peak at different temperatures with different VHG diffraction efficiencies.

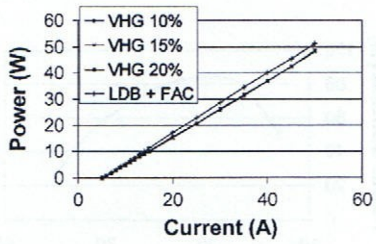

Fig. 11. *L–I* curves for the unlocked diode bar and the diode bar locked with three different VHG efficiencies.

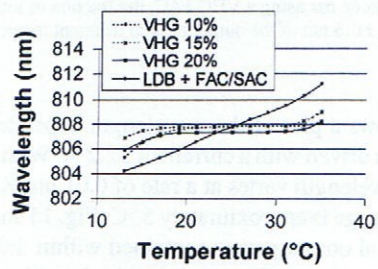

Fig. 12. Dependence of wavelength on temperature for locked and unlocked bars using a FAC and a SAC.

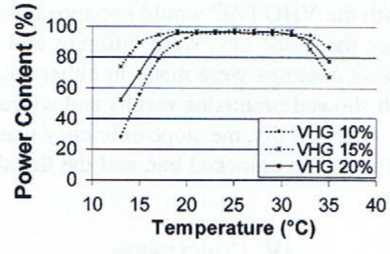

Fig. 13. For a diode bar using a FAC and a SAC, the fraction of total output power contained within ±0.5 nm of the output peak at different temperatures with different VHG diffraction efficiencies.

TABLE I
KEY PERFORMANCE METRICS FOR THE FAC AND FAC + SAC CONFIGURATIONS

Parameter	FAC Only	FAC + SAC
Locking Range	10 K	17 K
Fraction of power within +/- 0.5 nm of the peak (25 °C)	91.6%	98.5%
Wavelength-temperature dependence	0.011 nm/K	0.006 nm/K
Wavelength-current dependence	0.011 nm/A	0.008 nm/A
Threshold current	5.4 A	4.7 A
Slope	1.05 W/A	0.97 W/A
Losses at 25 °C	8%	13%

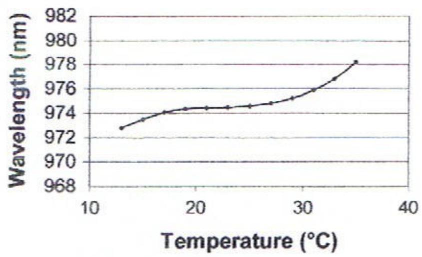

Fig. 14. Dependence of wavelength on temperature for a locked bar using a VHG FAC.

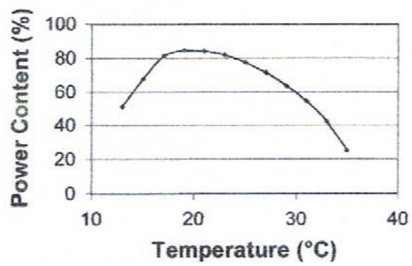

Fig. 15. For a diode bar using a VHG FAC, the fraction of total output power contained within ±0.5 nm of the output peak at different temperatures.

Fig. 14 shows a plot of the wavelength dependence on temperature when driven with a current of 32.2 A. Within the locked range, the wavelength varies at a rate of 0.01 nm/K. The locked temperature range is approximately 5 °C. Fig. 15 shows the fraction of the total output power contained within ±0.5 nm of the peak as the temperature is varied, and is also driven with a current of 32.2-A. The power content did not reach more than 85% at about 20 °C. Relative to the FAC-only configuration, the locking quality with the VHG FAC would not appear to be as good. However, since the diode bars were different and no attempts to optimize facet coatings were made in either case, the VHG FAC approach showed promising results and warranted further investigation. Additionally, the slope efficiency was reduced by only 3% relative to the unlocked bar, and the threshold current did not change.

IV. CONCLUSION

VHGs can be used in a variety of ways to stabilize the wavelength of LDs and LD bars. Although the technique is not new, advances in technology have now made the approach commercially feasible. There is room for optimization of the approach with regard to VHG diffraction efficiency, collimation quality, and facet reflectivity, by considering the tradeoffs between locking range, output spectrum, and power efficiency.

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Gregory J. Steckman (M'01) received the B.S. degree from the University of California, San Diego, in 1995, and the M.S. and Ph.D. degrees from California Institute of Technology, Pasadena, in 1997 and 2000, respectively, all in electrical engineering.

Currently, he is the Director of Engineering with Ondax, Inc., Monrovia, CA, and is responsible for the research and design of new products, volume holographic grating manufacturing, and test equipment. He is the Author or Coauthor of numerous publications on volume holography. He is the holder of four patents.

Wenhai Liu received the B.S. degree from Tsinghua University, Beijing, China, in 1992, the M.S. degree from the University of Chicago, Chicago, IL, in 1996, both in physics, and the Ph.D. degree in electrical engineering from California Institute of Technology, Pasadena, in 2001.

Currently, he is with Ondax, Inc., Monrovia, CA, working on product research and development. His current research interests include holographic technology and their applications in telecommunication and optical information processing.

René Platz is currently working toward the graduate degree in physical engineering (with a focus on optoelectronics/sensor technology) at the University of Applied Sciences, Jena, Germany.

Since March 2006, he has been with Jenoptik Laserdiode GmbH, Jena, Germany, on wavelength stabilization of high-power diode laser bars by external Bragg-gratings.

Dominic Schroeder received the Diploma in engineering physics from the University of Applied Science, Münster, Germany.

Since 2006, he is working with Jenoptik Laserdiode GmbH, Jena, Germany, as a Project Manager for packaging and qualification.

Christophe Moser (M'01) received the Ph.D. degree in electrical engineering from California Institute of Technology, Pasadena.

He is the Co-Founder and currently a CEO of Ondax, Inc., Monrovia, CA. Earlier he was in the Optical Measurement System Division of TESA-Brown & Sharpe, Switzerland. He was with Holoplex, an optical data storage startup, Pasadena, CA.

Frank Havermeyer received the Diploma and Ph.D. degree in physics from the University of Osnabrueck, Lower Saxony, Germany, in 1996 and 2000, respectively.

Currently, he is with Ondax, Inc., Monrovia, CA, working on the design and optimization of the production process of volume phase gratings for dense wavelength division multiplexing and general wavelength filter applications. Earlier, he was with GKSS Research Center, Bonn, and the University of Bonn, Bonn.