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Locking and wavelength selection of an ultra-collimated single-mode diode laser bar by a volume holographic grating

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Abstract: Wavelength-locking by a volume holographic grating (VHG) is reported for a diode laser bar with 49 single mode emitters, fitted with a dual-axis collimation phase-plate for smile elimination and excellent beam pointing correction. The much-improved VHG feedback with the ultra-collimated array beam gives 100% wavelength locking at 975 nm over a 17°C temperature range and external cavity lengths up to 110 mm. This enables a folded cavity configuration to provide a fully-locked array with wavelength selection into 200 pm channels over an 8 nm band, suitable for multi-bar dense wavelength-combining.

References and links

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1. Introduction

Efficient wavelength locking of laser diode arrays to a selected, narrow spectral line enables dense spectral beam combining [1] of large numbers of emitters and multiple laser bars. Generally, to achieve optimised performance with beam combining and line narrowing techniques, the diode laser source should have good single emitter brightness and co-alignment of the individual emitter beams. In particular, laser bars should have low smile-induced collimation errors. Single lateral mode emitters provide the highest brightness for beam combining, as narrow-stripe ridge waveguides of 3-6µm lateral width or as aperture tapered devices of larger aperture with a higher power per emitter. For laser arrays in an external cavity, accurate slow-axis collimation and a uniform feedback distribution for all the emitters become particularly challenging.

In a previous paper [2], we presented a technique for "ultra-collimation" of laser diode bars by using a single laser-written phase-plate to correct fast-axis collimator (FAC) lens errors and bar smile as reported previously in [3], but now integrating an array of matched slow-axis collimator (SAC) lenses. We applied such a dual-axis phase-plate to a 49 single-mode emitter bar with emitter spacing of 200 µm. The achievement of maximised single beam quality combined with close matching of the pointing direction of all beams in both axes now has the potential to enhance the performance of a range of techniques for spatial and

spectral brightness improvement of laser diode arrays. These include spatial multiplexing, phase-locking, line narrowing and spectral beam combining. The aim in this paper is to show that ultra-collimation of diode bar radiation enhances wavelength-locking by a volume holographic grating (VHG), enabling an efficient, low-loss locking technique using a single VHG to create an array of narrow spectral lines suitable for dense wavelength combining.

Here we report the enhancement of VHG wavelength locking and tunability of an array of 49 single-mode emitters with 200 μm pitch and reduced reflectivity facets (~10^{-4}) in an external cavity configuration. VHGs represent a competitive alternative to the commonly-used techniques of wavelength locking and tuning with conventional diffraction gratings in the Littman/Littrow configurations, because of their high spectral selectivity and diffraction efficiency. Although a single VHG acts as a spectral filter optimized for one particular wavelength, wavelength selection can be achieved by VHG angular tuning [4]. Here we show that the precise array collimation enables efficient locking over the full range of temperatures available in our equipment, and additionally this is maintained for large distances between the bar and the VHG. We go on to demonstrate a folded cavity configuration in which better control of feedback allows the achievement of uniform locking and wavelength selectivity over a range of 8 nm using a single, angle-tuned VHG.

2. Experimental setup for VHG-locking of a single-mode emitter bar

The laser used in our work is a passively-cooled, 49 single-mode emitter bar supplied by Oclaro, producing 30W at 40A. Each emitter has an aperture of 1 x 6 μm^2 and a 3.6 mm cavity length, providing a maximum power output of 0.61W at 975 nm in a good single spatial mode. The laser was collimated by a conventional 0.6 mm focal length FAC lens for which a smile offset of 3.8 μm peak-to-valley resulted in an initial 6 mrad (peak-to-valley) pointing variation along the bar. The laser bar was scanned using a wavefront sensing technique to provide data to implement fast-axis correction [3]. Separate refractive plates, laser written in silica glass, were custom-fabricated by PowerPhotonic Ltd to provide (1) fast-axis (FA) error correction, (2) a 200 μm pitch, 0.9 mm focal length SAC array and (3) combined FA correction/SAC array, as described in [2]. The FA correction reduced the pointing errors to 75μrad (RMS), and the far-field divergence of the full bar was measured to be 2.47 mrad (5-95%) corresponding to a beam propagation factor value of M^2~1.3. The integrated slow-axis collimation with lens array focal length of 0.9 mm produced a divergence of 17 mrad (5-95%) with the pointing directions of all the emitters enclosed within 10% of the far-field divergence.

For this particular type of array, we investigated the impact of high pointing accuracy and high quality collimation on the feedback efficiency in a VHG locking configuration, and including cases when the VHG is positioned at large distances from the emitter plane. The experimental configuration contained the FAC-lensed laser bar, interchangeable phase-plates that provided one of the three functions described above and a reflective VHG placed at distance L from the front face of the optics. The VHG was supplied by Ondax Inc., with 200 pm FWHM bandwidth and diffraction efficiency (DE) of 15%. In Fig. 1, the external cavity for a one emitter in the bar is shown separately for slow- and fast-axis.

In such a cavity, the VHG diffracted feedback must out-compete other sources, such as that from the output facet of the bar or reflection from the collimating lens surfaces, to ensure a large locking range. Ideally, the light reflected by a closely positioned VHG may be fully coupled back on to an emitter after passing through the collimating optics a second time. However, any pointing errors of the collimated beams caused either by smile offset in the fast-axis direction or lens array mis-registration in the slow-axis direction (see [2]) will result in displacement of the feedback beam at the laser facet which can significantly decrease the fraction of the feedback beam that is effectively coupled into the fundamental mode of the waveguide, as in Fig. 1(a) for the fast-axis. Additionally, as illustrated in Fig. 1(d) for the slow axis, the returning diverging beam may be truncated by the limited aperture of the

collimating optics as the VHG distance L is increased, creating diffraction ripples in the far-field profile at the diode facet as in Fig. 1(c), reducing the power coupled back into the emitter. For the densely packed single-mode bar this is particularly evident in the slow-axis direction due to high divergence in the slow-axis after collimation and the small active width of the SAC lens (170µm) [2]. For the case of a bar of single-mode emitters, good spatial properties and co-alignment of the beams are particularly critical if high efficiency and uniform coupling to all small aperture emitters in the bar are to be achieved.
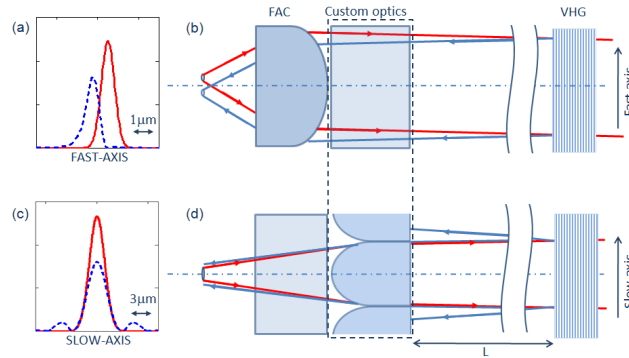

Fig. 1. Schematic diagrams of the external cavity configuration and corresponding beam profiles before and after a round trip, for fast-axis in (a) and (b) and slow-axis in (c) and (d).

For the VHG-locking configuration in Fig. 1, the overall fraction of light fed back to the emitters is a product of the feedback efficiency in both axes and the VHG reflectivity. Also, the amount of light diffracted by the VHG depends on its angular and spectral acceptance. The minimum feedback level required for locking is determined by the required locking range, defined by the difference between the 'natural' wavelength and the Bragg wavelength of the VHG. For a close match between the VHG and natural lasing, this can be provided by the light scatter associated with angular spread due to lens aberrations. However, to realize a practical wavelength-locked system, the optical coupling among emitters in the array must be kept at a high and uniform level, thus allowing the use of a VHG with lower DE. In this way, the power loss can be minimized whilst maintaining good locking and improving the thermal stability and the acceptable wavelength detuning range.

The performance of VHG-locking of the bar was studied using simultaneous recording of *both* the spatial properties and spectra for each emitter along the bar. For rapid evaluation of VHG locking quality, a Czerny-Turner imaging spectrometer produced a live view of the wavelength distribution along the bar as in Figs. 2(a)-2(c). Images from the CCD camera are processed to provide the fraction of the bar power within a ± 150 pm range from the mean wavelength, and this is used as the numerical measure of locking efficiency for the examples in Fig. 2 and in the study presented in Section 3. A reduction of locking efficiency indicates that either some of the emitters begin to generate part of their light beyond the locked spectrum or go completely out of lock and lase on their natural wavelength. Figure 2 provides three examples of the emitter resolved spectra observed during the experiments, (a) a fully locked case (100%), (b) partially locked (93%) and (c) an unlocked bar (30%, due to natural lasing at the Bragg wavelength). For calibration and higher resolution spectral analysis (60pm FWHM), a fibre-coupled spectrometer (0.5m SPEX) was used with single emitter selection achieved by moving the fibre end through a near field image of the bar. This setup provides information on the uniformity of wavelength distribution along the bar and has sufficient resolution to resolve the longitudinal mode emission from individual emitters. An example of locked and unlocked spectrum of a single emitter is shown in Fig. 2(d).
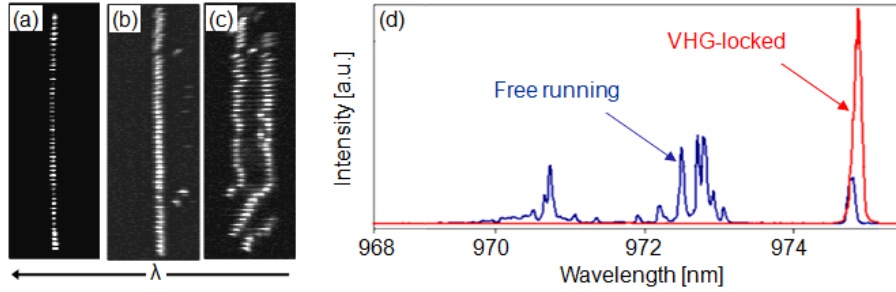
Fig. 2. Imaging spectrometer view of bar emission when (a) fully-locked (b) partly-locked and (c) unlocked. (d) High resolution spectrum for a sampled single emitter

3. Efficient, uniform locking of the single mode emitter bar

Here we study the impact of accurate dual-axis collimation on feedback efficiency in the VHG locking configuration by investigating the locking efficiency for different degrees of collimation. In Fig. 3(a) the locking efficiency is shown as a function of the temperature at the laser mount, with the VHG placed at a distance of 3 mm from the laser facet. The results show that the bar with only a FAC locks-up over only a narrow range of temperatures, since only a small fraction of the un-collimated slow axis beams can be fed back to their emitters. Correcting for fast-axis smile error improves matters a little. However, addition of slow-axis collimation increases feedback substantially, and a more useful temperature range for 100% locking is now obtained. Finally, the insertion of the combined-function phase-plate which provides excellent smile correction as well as dual-axis pointing accuracy allows the VHG to yield uniform, 100% locking for the maximum temperature range of 13-30°C permitted by the available hardware.
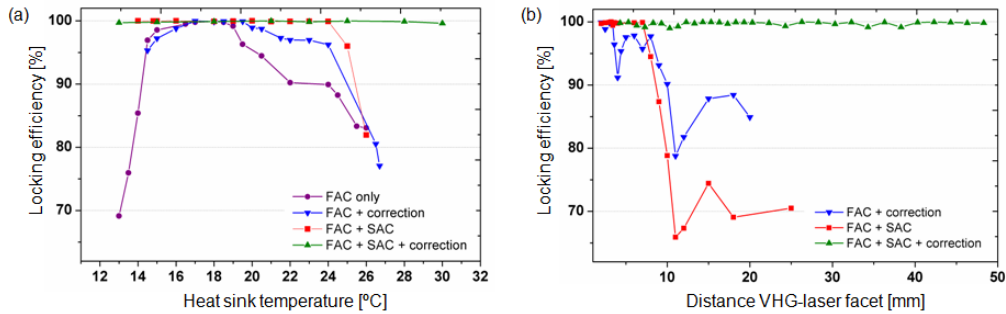

Fig. 3. Efficiency of VHG locking with DE = 15% (a) as a function of temperature of the heat sink with VHG placed at 3 mm distance from the laser and (b) distance between the VHG and laser facet for 0.6 nm VHG offset.

In a second experiment, locking efficiency for different degrees of collimation was measured as a function of the emitter-VHG distance, with the natural laser wavelength temperature-tuned to 0.6 nm from the Bragg wavelength, as in Fig. 3(b). Using the FAC lens only, or with smile correction added as in Fig. 3(b), 100%-locking of the bar could only be achieved with the VHG located less than 4 mm from the emitter facet. When slow-axis collimation was added but with uncorrected smile error, the maximum distance for 100% locking increased to 8 mm. Beyond this point, some emitters were observed to go out of lock due to the significant pointing error induced by the smile. However, when both smile and slow-axis corrections were provided, 100% locking was maintained at distances up to 48 mm.

For the case with the bar fitted with the phase-plate providing smile correction and accurate collimation in both directions, we investigated the VHG alignment sensitivity by recording the VHG angular locking range where all the 49 emitters remain fully locked to the

Bragg wavelength. We found that the misalignment tolerance in the slow-axis direction varies from 2 mrad off-axis angle for the VHG at a distance of 40 mm from the laser to 6.5 mrad for 12 mm distance. In the fast-axis direction, tilt of as little as 2 mrad is sufficient for the first observation of emitters emitting at their natural wavelength, but the angular acceptance remains roughly unchanged over the range of emitter-VHG distances investigated in Fig. 3. These tilt-sensitivity measurements were initially taken with the laser temperature-tuned to about 4.5 nm from the Bragg wavelength. For a spectral detuning reduced 2 nm and a laser-VHG distance of 12 mm, the angular acceptance increased to about 3 mrad in the fast-axis and 15 mrad in the slow-axis, consistent with the smaller amount of feedback required to pull all the laser radiation to the Bragg wavelength.

   Our results show that high pointing accuracy and good collimation enable highly efficient feedback in the external cavity configuration enhancing the locking range. In particular, slow-axis collimation with low pointing error is essential for good feedback to the small aperture of the single-mode emitters. Correction of smile is clearly effective at extending the temperature range of 100% locking and is essential for large distance VHG locking. The efficient distant-locking enables the work on wavelength selection in a folded cavity configuration presented in the next section.

4. Wavelength selection in folded cavity configuration

Figure 4 illustrates a cavity configuration that uses the VHG as a folding mirror, with angular tuning of the Bragg condition to obtain wavelength selection for the full bar using a single VHG. A high reflectance (HR) plane mirror is placed beside the bar collimating optics and feeds back the diffracted beam for a second diffraction at the VHG, returning it through the collimation optics which focus it on the exit apertures of the emitters. In a similar tuning approach for a single, broad area emitter, Moser et al. [4] placed the feedback mirror at a smaller distance beside the emission area of the laser diode, at the back focal plane of the FAC lens. In that set-up, the tuning range was limited geometrically to less than 1 nm by the aperture of the collimating lens and the size of the HR mirror, with feedback potentially being reduced also by optical aberrations from the four passes through the FAC lens. Using the large-distance locking capability established in Section 3, our configuration allows a much wider range of angular tuning. The minimum detuning from the wavelength at normal incidence is determined by the gap between HR and collimating optic. However, this is minimized for large laser-VHG distance L.
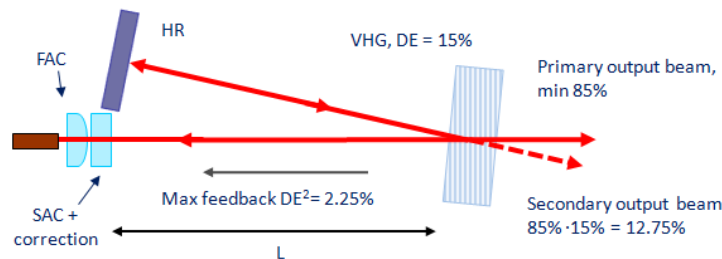

Fig. 4. Experimental setup for wavelength selection in a folded cavity with a VHG.

   In Fig. 4, the VHG was placed with L = 55 mm, and the initial locked wavelength was 974.4 nm at normal incidence, with the laser temperature chosen to be 14.4°C. This matched the natural laser wavelength to the centre of the tuning range, thereby maximizing the range of wavelengths that could be obtained. Subsequently, the VHG, and correspondingly the HR mirror, were rotated to form folded cavities in which a range of Bragg wavelengths could be fed back to the emitters. In Fig. 5, this range of fully-locked wavelengths points is plotted against selected angles of rotation of the VHG away from normal incidence.

We obtained angular tuning of the VHG over a 12 degree range producing wavelength selection over an 8 nm band, agreeing with the expected small angle variation of the Bragg wavelength between 2 and 12°. Emitter-resolved spectra at points A and B in Fig. 5 represent the two ends of the detuning range within which all the emitters were locked to the selected Bragg wavelength. At the ends of the range some emitters start to show their natural wavelength, most of the power (>98%) is still contained within the locked spectrum. Point C illustrates the effect of a temperature change to 23.3°C, shifting the natural spectrum to 7.2 nm from the Bragg wavelength at this VHG angle, with partial locking still evident. The maximum detuning range at 14.4°C was ± 4 nm, smaller than the >5 nm range reported in Section 3 for normal incidence at the VHG. This is explained in terms of reduced VHG feedback in the folded cavity, as indicated as part of Fig. 4. The beam is diffracted twice and the maximum effective diffraction is equal to DE^2, where DE is the diffraction efficiency of the VHG. This also results in the secondary output beam shown, which contains significant power. A drop-off in locking efficiency at the largest angles may also be associated with reducing VHG diffraction efficiency for a narrow Gaussian beam incident at angle [5].
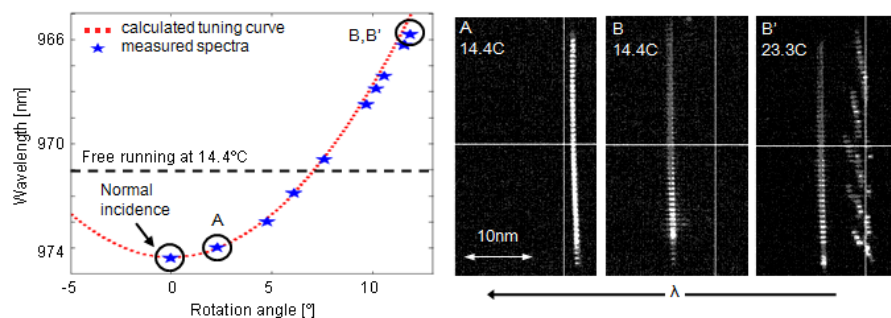

Fig. 5. Wavelength vs. angle of the VHG obtained in the folded cavity configuration and examples of measured spectra. The laser was operated at 20A of drive current. (Note: the non-uniform intensity pattern and a slight tilt of the image are due to aberrations in the imaging system.)

5. Conclusion

We have shown that laser-written corrective phase-plate technology and ultra-collimation [2] gives substantial enhancement in both diode temperature and VHG distance locking ranges for single mode emitter diode bars, with 100% locking of all 49 emitters achieved up to a 110 mm feedback mirror distance. The results are evidence that uniform and efficient feedback delivery is achieved. Full-bar wavelength locking over a wide range of bar temperatures is directly valuable for applications where stable thermal conditions cannot be ensured. The distance enhancement directly enables the new configuration of VHG folded cavity with angular wavelength selection. An 8 nm tuning band with 100% locking to within a 200 pm bandwidth is obtained stably. As a future outlook, potentially up 20 individually tuned bars may be wavelength combined using a grating combiner as in [1] followed by incoherent beam shaping, to make an ultra-bright source for direct-diode laser applications. Extension to locking of bars with brighter, tapered single-mode emitters is also an exciting prospect.

Acknowledgments