A novel tunable diode laser using volume holographic gratings

Christophe Moser* , Lawrence Ho and Frank Havermeyer
Ondax, Inc. 850 E. Duarte Road, Monrovia, CA 91016, USA

ABSTRACT

We have developed a self-aligned external cavity laser with a non-dispersive volume holographic grating (VHG) as the output coupler. The resulting external cavity is tunable by rotating the VHG. We have demonstrated tunable single mode longitudinal operation at 405 nm and 785 nm wavelength. The passive alignment of the novel tunable laser is the main driver for achieving low cost manufacturing. The axial symmetry enables the use of axially symmetric components such as TO-can laser packages, lenses and VHGs which further reduces the cost of manufacturing and the laser footprint.

Keywords: single frequency lasers, laser diodes, external cavity, tunable, volume holographic gratings, self-aligned, passive alignment.

1. INTRODUCTION

State-of-the-art Littrow and Littman external cavity lasers (ECL) use an angularly dispersive surface diffraction grating as the frequency selective element and a rotation scheme to provide wavelength tuning [1]. Although miniaturization of ECLs have been attempted commercially at the 1.5 μm telecommunication wavelength, footprint reduction has been difficult to realize at shorter wavelength. The main reason is that shorter wavelength requires higher spectral resolution and this tends to increase the size of the optics.

In contrast to the Littman and Littrow cavities, fixed wavelength ECLs using non-dispersive reflection volume holographic gratings (VHG) have been reported for the first time to the authors' knowledge in 1985 [2]. Since then, others have made fixed wavelength ECLs using VHGs for single mode and multimode high power lasers [3-6]. Although passive alignment of an ECL with VHGs has been demonstrated [4], such an ECL is tunable only by controlling the temperature of the VHG, which limits the tuning range to a few tenths of a nanometer. The current study demonstrates both passive alignment and large tuning range using VHGs.

2. DISPERSIVE AND NON-DISPERSIVE EXTERNAL LASER CAVITIES

In the Littrow cavity (Fig.1(a)) the diffraction grating, typically blazed, retro-reflects the diffraction order back in the direction approximately opposite to the incoming collimated beam. The zero order of the diffraction is the output of the cavity. The spectral resolution of the Littrow laser cavity is given by [7].

$$\Delta\lambda_{Littrow} = \frac{\lambda^2}{\pi \cdot D_o \tan\beta} \ , \quad (1)$$

where λ is the wavelength of the laser, D_o is the diameter of the collimated beam at the waist and β is the angle formed by the normal of the dispersive grating and the direction of the collimated beam. As can be noted from equation 1, for maximum spectral resolution, the diameter of the beam should be as large as possible and at a grazing angle on the dispersive grating. A larger beam diameter increases the cavity length since either a longer focal length or intra-cavity prism expanders are required.

*moser@ondax.com; phone 1 626 357 9600; fax 1 626 357 9321; ondax.com

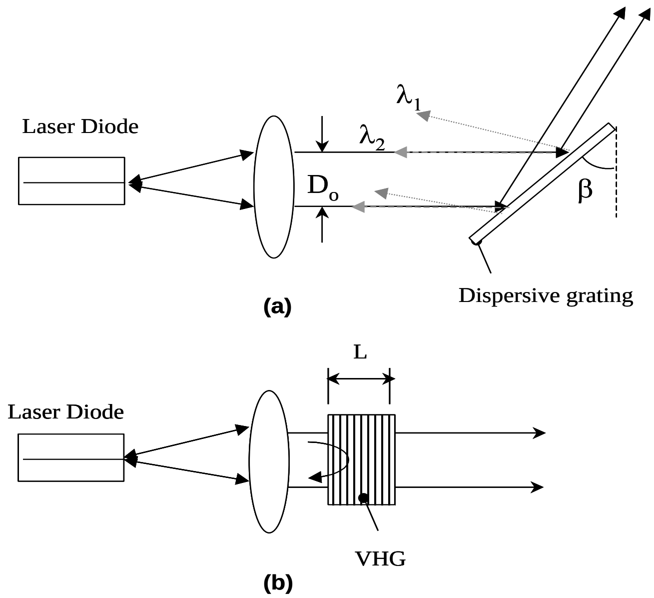


Fig. 1. (a) Littrow ECL with dispersive grating (b) ECL based on non-dispersive VHGs.

Figure 1(b) shows an ECL based on a non-dispersive VHG for the spectrally selective component in the cavity [1]. The VHG acts as a narrowband reflective output coupler, which filters and reflects only a spectrally narrow portion of the light back into the laser diode. The spectral resolution of a reflective VHG is given by [8]:

$$\Delta\lambda_{VHG} = \frac{\lambda^2}{\pi \cdot L}, \qquad (2)$$

where L is the interaction length of the VHG.

In equation (1), the expression $D_o \cdot \tan\beta$ is the projection length in the direction of the incident beam of the beam's intercept on the dispersive grating (see Fig. 1(a)). Equation (1) and (2) are then identical in form, however there is a significant difference in the design implications for the external cavity.

- The spectral resolution of a dispersive ECL (eq. 1) is dependent on the collimated beam diameter. It results from the divergence of a diffraction limited collimated beam and the angular dispersion of the grating illuminated.

- In contrast, the spectral resolution of a non-dispersive ECL (eq. 2) is independent of the collimated beam diameter. This is because the reflective VHG is not dispersive and the laser diode emission area forms a spatial filter. The implication for the external cavity is that the collimated beam size can be small (small focal length) to reduce the physical cavity length of the ECL.

3. NON-DISPERSIVE SELF-ALIGNED LASER CAVITIES

A modification of the architecture shown on Fig.1(b) is proposed to remedy the drawbacks of active alignment and lack of tunability of previous external cavity based on VHG [9]. The novel external cavity laser is shown schematically in Fig.2(a). The reflective VHG has a slanted grating (grating vector not orthogonal to the facet of the VHG). The orientation of the VHG is purposely misaligned to produce a diffracted beam that is not parallel to the incident beam. The collimating lens focuses the diffracted beam on a mirror positioned at the focal plane at a distance from the emission facet of the laser diode. Upon reflection from the mirror, the beam is collimated a second time and diffracted a second time to produce a beam that is exactly counter-propagating with the initial collimated beam. The double diffraction arrangement ensures that the second diffracted beam is propagating back in the laser diode and thus the VHG is self-aligned in the sense that any orientation of the VHG produces feedback in the laser diode cavity. A second output beam is generated from the un-diffracted beam from the second diffraction.

Wavelength tuning can be achieved, for example, by rotating the VHG around an axis perpendicular to the VHG's facet and a few degrees off the optical axis. In this case, rotating the VHG does not change the output beam direction or beam walk-off (provided the two opposing facets of the VHG are parallel). It does, however, change the angle θ between the collimated beam and the grating wave vector and will therefore tune the feedback wavelength λ according to $\lambda = \lambda_0 \cdot \cos\theta$, where λ_0 is the diffracted wavelength when the direction of the incident light is parallel to the grating wave vector ($\theta = 0$).

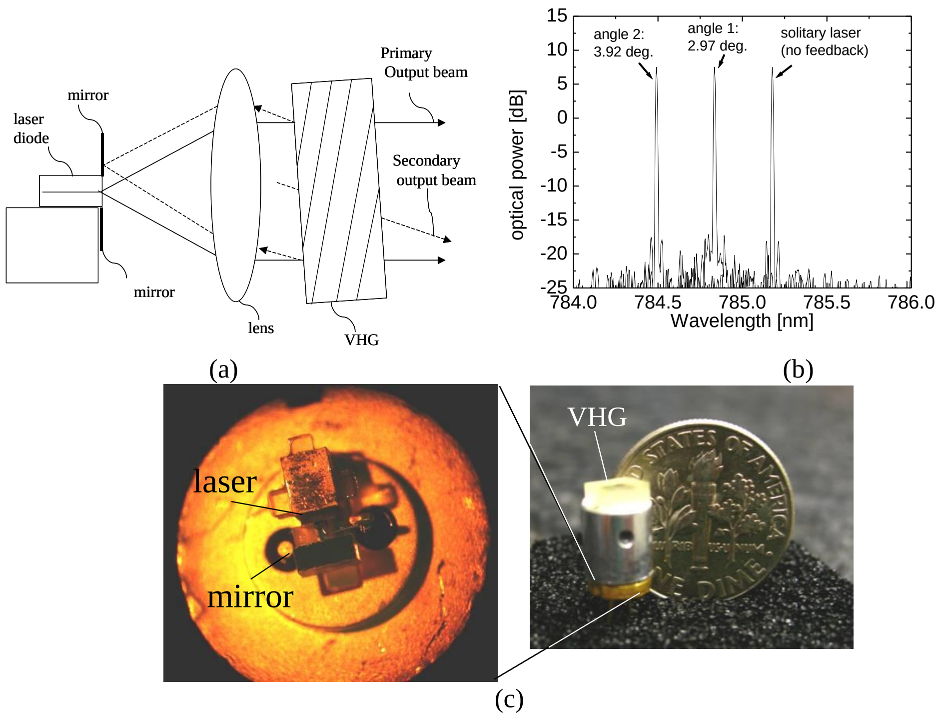
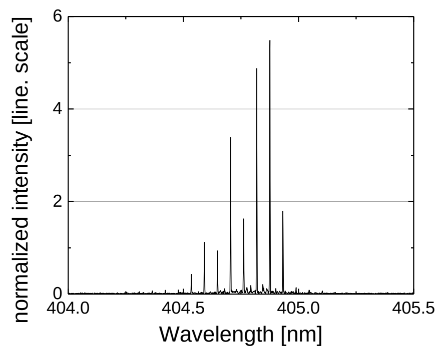
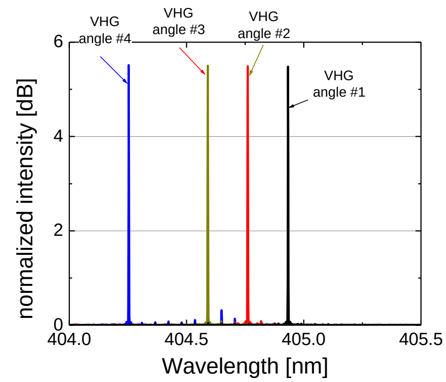


Fig. 2. (a) Self-aligned External Cavity architecture. (b) Single frequency mode spectra of the solitary laser and for two rotation angles of the VHG (c) Picture of the collimated ECL with a VHG mounted on top in a fixed wavelength configuration.

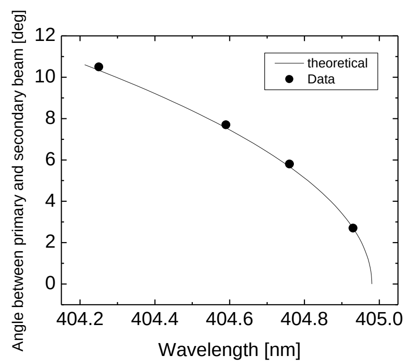
Figure 2(b) shows the single frequency spectrum for three rotation angles of the VHG. The laser single frequency operation was verified by the spectrum obtained with an optical spectrum analyzer with 10 pm resolution. The linewidth was not measured. The diode laser is an off-the-shelf 80 mW single mode Fabry-Perot laser with standard facet coating (>10%). The lens is a 3.6 mm focal length AR coated radial gradient index lens. The side mode suppression ratio achieved for the ECL is 25dB. Fig.2(c) left shows a picture of a TO-can 5.6 mm laser diode with a 1 by 2 μm emission facet area and with a mirror mounted adjacent the emission facet. Fig.2(c) right shows the TO-can laser diode mounted in a tube holding a collimating lens inside and with the VHG mounted on top. The mirror is mounted approximately 0.3 mm above the laser chip and has a dimension of 0.3 mm by 1 mm. The VHG was adjusted without any fine angular alignment stages. Wavelength tuning was achieved by mechanically rotating the 30% efficiency VHG in front of the collimated laser diode. As long as the diffracted beam is reflected off the mirror area, the secondary beam is visible and the wavelength corresponds to the VHG angle. The tuning range achieved in the prototype is 0.75 nm and was limited by the size of the mirror in the short direction (0.3 mm). The measured power in the secondary beam is 15% of the primary beam power. This value is consistent with a 30% efficiency grating since after two diffractions, the transmitted secondary beam power fraction is the product of the grating efficiency and the transmitted efficiency (60% · 30% = 18%).



(a)



(b)



(c)

Fig. 3. (a) original diode spectrum of a 10 mW, blue-violet 405 nm laser diode (b) spectra of the ECL at different VHG angles. (c) angular wavelength tuning of the VHG in the plane of Fig. 2. Angles are measured between the output beam and the secondary beam (values are twice the rotation angle of the VHG)

Similarly, the self-aligned external cavity has been demonstrated on a blue-violet laser diode, 10 mW at 405 nm. The laser diode has a standard front facet coating of 10% reflectivity. Fig.3(a) shows the spectral characteristic of the solitary laser diode without feedback. Fig. 3(b) shows the single frequency mode spectrum when feedback is applied with a VHG at several angles (VHG has 35% reflectivity and 4mm length, focal length of collimated lens 4 mm). For the spectrum centered at 404.25nm, the side modes corresponding to the solitary laser diode are suppressed by 15dB but still visible. We expect the side modes to decrease further and the tuning range to increase with good laser diode front facets coatings (<0.1%).

The tuning range is limited by the numerical aperture of the collimating lens and the size of the mirror. In a Littrow cavity, the wavelength varies as $m\lambda = 2 \cdot \Lambda \cdot \sin\alpha$, where m is the diffraction order, Λ the groove spacing and α the angle between the incident beam and the normal to the grating. Typically, in the Littrow cavity α is in the range of 30 degrees and with the VHG cavity the angle θ is typically between 0 and 15 degrees. Thus, the wavelength of this tunable VHG-ECL cavity is less sensitive to the VHG rotation angle in comparison with a Littrow cavity.

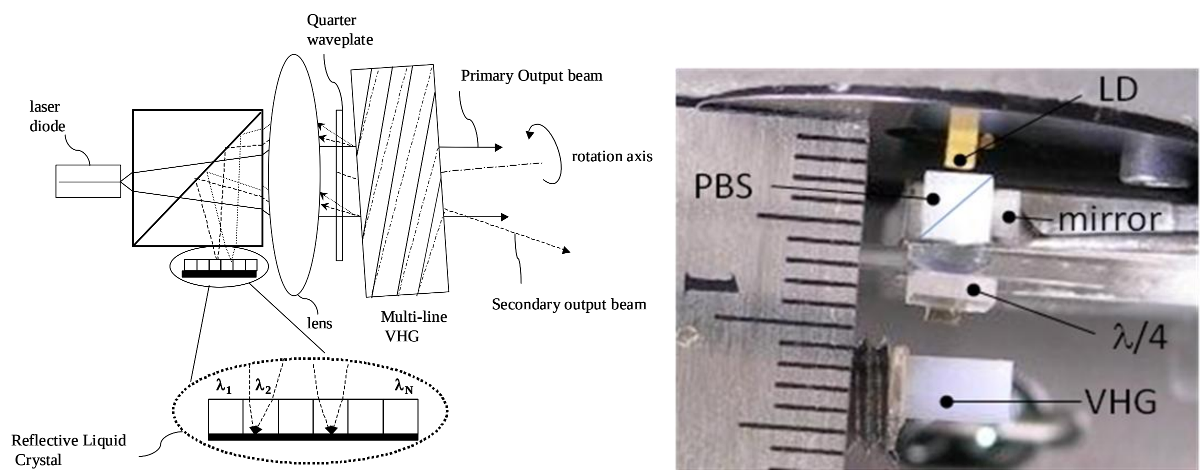
The VHG-ECL design described in section 4 below provides an extended tuning range.

4. EXTENDED TUNING RANGE DESIGN

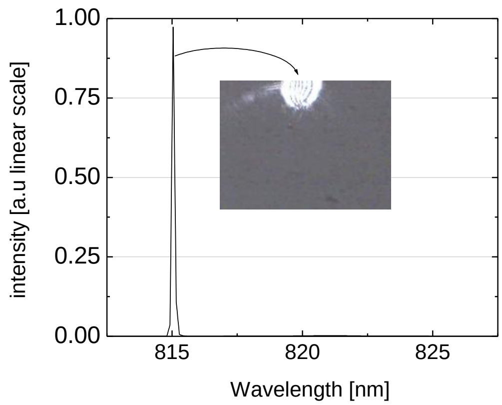
Fig.4(a) illustrates the cavity design that increases the tuning range to several tens of a nanometer by taking advantage of the grating multiplexing property of VHGs. A total of *N* gratings are multiplexed in the VHG, each with a specific grating vector $\mathbf{K}_i$, i=1,…,*N*. For each direction of the grating vector, there corresponds a spatial location in the focal plane of the collimating lens. The working principle of this self-aligned tunable ECL is the following: each of the *N* multiplexed gratings in the VHG diffracts a specific longitudinal mode. An amplitude or polarization modulator positioned at the focal plane of the lens induces high loss for all the modes but one, allowing only one mode to exist in the cavity.

The polarized beam from the laser diode is oriented such that the beam propagates through the polarizing beam splitter. A double pass through the quarter waveplate rotates the polarization of the diffracted beams by 90 degrees, such that the polarizing beam-splitter reflects the diffracted beams towards a polarization modulator, for example, a reflective liquid crystal (LC) cell. With the proper voltage on the LC cells, the polarization of each diffracted beam can be rotated by 90 degrees or left unchanged. The beams whose polarization directions are rotated by 90 degrees are transmitted through the polarizing beam-splitter and experience a high loss in the cavity compared with the beams whose polarization are left unchanged.

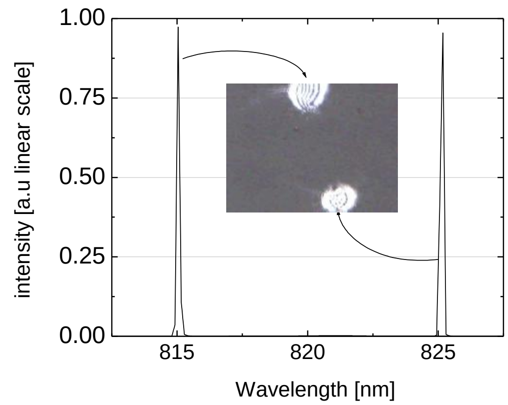
A discrete wavelength tuning range is achieved with this ECL with no moving parts by switching the beams with the LCD. The number of discrete wavelengths is equal to the number of multiplexed gratings in the VHG. Wavelength tuning between the discrete wavelengths is achieved by rotating the VHG. Currently, with the glass holographic material, approximately 50 multiplexed gratings with approximately 20% efficiency can be manufactured, which would yield a tuning range of 25 nm with 0.5 nm spacing.



(a) (b)



(c)



(d)

Fig. 4. (a) Extended wavelength tuning range self-aligned ECL based on multiplexed gratings. (b) Experimental demonstration of the concept with a two line VHG and a reflective mirror in place of the LCD. (c,d) experimental results: the two modes of the cavity corresponding to the two multiplexed gratings are simultaneously competing. The insert is an image of the secondary beams.

Figure 4(b) shows an implementation of this cavity where the LCD is replaced by a flat mirror. A multiplexed 3mm-thick VHG was fabricated with two gratings at 815 nm and 825 nm, each with diffraction efficiency of 45% . The slant angle of the two grating is respectively 2 and 4 degrees. The laser diode (EagleYard, EYE-RWE-840) has a front facet AR coating <0.1% reflectivity. The flat mirror in fig. 4(a) reflects both diffracted beams. The two laser frequencies are competing in the laser cavity. Fig. 4(c) shows an instance of the single frequency near 815 nm oscillating whereas fig. 4(d) illustrates both frequencies oscillating. The insert in fig. 4(c,d) illustrated the secondary beams captured by a CCD camera. The angular separation of the two beams caused by their slant angle difference corresponds to a physically distinct location of the beam on the camera. We verified that by rotating the VHG, fine wavelength tuning was achieved similarly to the tuning achieved in section 3.

CONCLUSIONS

We have experimentally demonstrated a self-aligned external cavity based on double diffraction from a VHG for generating tunable single frequency operation in a compact package length (14mm) at 405 nm and 785 nm wavelength. The simple and compact external cavity is wavelength tunable over 0.8 nm by rotating the VHG. A laser cavity with an extended tuning range is presented and experimentally demonstrated with a 10 nm range and which allows discrete wavelength tuning without moving parts.

This self-aligned cavity design removes the tight angular tolerance that was required to align the VHG in previous fixed and tunable external cavity architectures. This laser cavity architecture can be used in a broad wavelength range from 375 nm to 2500 nm.

REFERENCES

1. **P. Zorabedian et. al. "Alignment-stabilized grating-tuned external cavity semi-conductor laser," Opt. Lett. 15, 9 pp. 483-485. (1990).**
2. **P. Mills "Single mode operation of 1.55 μm semi-conductor laser using a volume holographic grating," Electron. Lett. 21, 15 pp 648-649. (1985).**
3. **B. Volodin et. al "Holographic volume Bragg gratings stabilize laser diode performance," Photonic Spectra 37 , 11 pp. 68-70. (2003).**
4. **G. Steckman et. al. "Volume holographic grating wavelength stabilized laser diodes," J. Sel. Top. Quantum Electron. 13, 3 pp. 672-678. (2007).**
5. **L. Glebov et. al "High-brightness narrow-line laser diode source with volume Bragg-grating feedback,"** ***in Proceedings of the SPIE (*****San Jose, CA, USA,2005), vol. 5711, issue 1, pp. 166-76.**
6. **S. Rudder et. al "Hybrid ECL/DBR wavelength & spectrum stabilized lasers demonstrate high power & narrow spectral linewidth"** ***in Proceedings of the SPIE (*****San Jose, CA, USA,2006), vol. 6101, pp. 82-86.**
7. **Y. Cunyun "*****Tunable External Cavity Diode Lasers,*****" (World Scientific press, 2004), page 80.**
8. **H. Kogelnik, "Coupled waved theory for thick hologram gratings," Bell Syst. Tech. J. 48, 9 pp. 2909-2947 (1969).**
9. **C. Moser et. al. "Self-aligned non-dispersive external cavity tunable laser", Opt. Exp. 16, 21, pp. 16691-16696 (2008).**