Self-aligned non-dispersive external cavity tunable laser

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Abstract: We are reporting on a novel self-aligned non-dispersive external cavity laser (ECL) based on thick volume holographic gratings (VHG). The ECL is tunable and operates with single mode and broad area multimode laser diodes. We experimentally demonstrate tunable single frequency operation at 405 nm and 785 nm. The tunable ECL concept is also experimentally tested with high power broad area laser diodes near 780 nm. The passive alignment feature of the cavity is expected to reduce the assembly cost of tunable ECLs.

OCIS codes: (140;2020) Diode lasers; (090.4220) Multiplex holography

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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 [1,2,3]. Although miniaturization of ECLs have been attempted commercially at the 1.5 μm telecommunication wavelength using MEMs to rotate the components [4], footprint reduction has been difficult to realize at shorter wavelength. The

#101190 - $15.00 USD Received 5 Sep 2008; revised 1 Oct 2008; accepted 2 Oct 2008; published 3 Oct 2008

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 [5]. Since then, others have made fixed wavelength ECLs using VHGs for single mode and multimode high power lasers [6-9]. Although passive alignment of an ECL with VHGs has been demonstrated [8], 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. Comparison of the spectral resolution of ECL with dispersive and non-dispersive gratings.

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. Schemes to stabilize the alignment sensitivity have been devised by introducing optical elements such as cylindrical lenses between the collimated lens and the diffraction grating [2]. A disadvantage of the Littrow cavity is that angular tuning of the diffraction grating also changes the direction of the output beam. The spectral resolution of the Littrow laser cavity is given by [10].

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

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 intracavity prism expanders [3] are required.

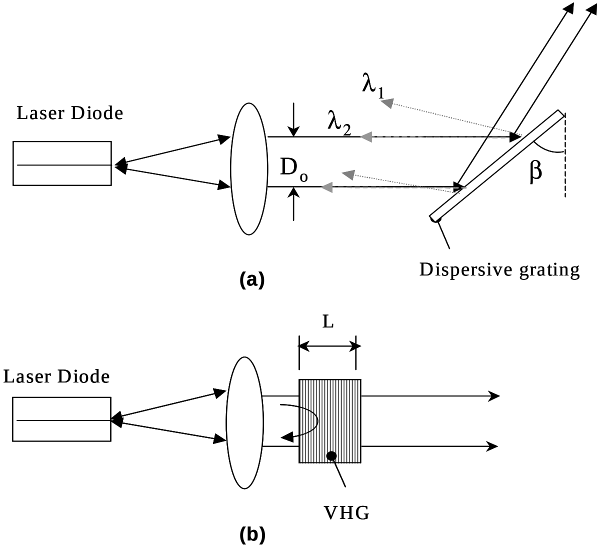


Fig. 1. (a) Littrow ECL with dispersive grating (b) ECL based on non-dispersive VHGs.

Figure 1(b) shows an ECL based on a non-dispersive VHG for the spectrally selective component in the cavity [5]. The VHG acts as a narrowband reflective output

Received 5 Sep 2008; revised 1 Oct 2008; accepted 2 Oct 2008; published 3 Oct 2008

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 [11]:

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

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. The impact of a small collimated beam is a reduced effective coupling efficiency in the laser diode. This can be alleviated by increasing the diffraction efficiency of the VHG.

3. Passively aligned ECLs with volume holographic grating

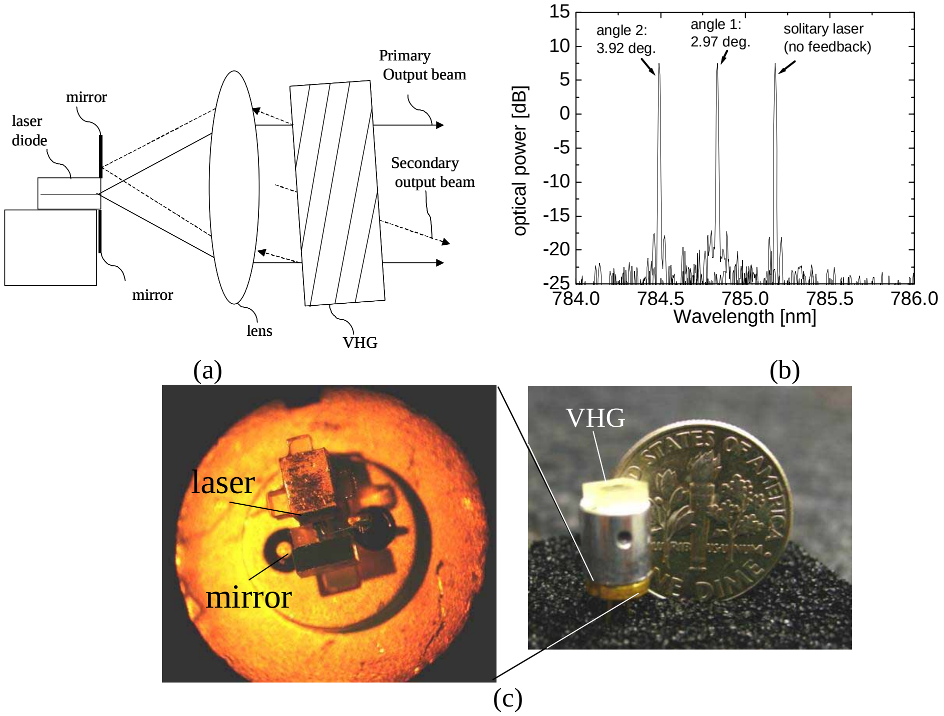
A modification of the architecture shown on Fig.1(b) is proposed to remedy the drawbacks of active alignment and lack of tunability of previous external cavity based on VHG. The novel external cavity laser is shown schematically in Fig.2(a). The reflective VHG has a slanted grating (grating vector not 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 feed back 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 ($\theta = 0$). 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.

#101190 - $15.00 USD Received 5 Sep 2008; revised 1 Oct 2008; accepted 2 Oct 2008; published 3 Oct 2008

The beam reflecting off the mirror is displaced, at the lens position, by an amount equal to the distance between the laser diode emission point and the location of the focus of the diffracted beam on the mirror. At large diffraction angles, the lens may partially obstruct the re-collimated diffracted beam.



(a) (b)

(c)

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%).

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The ECL design concept is then applied to a broad area high power laser with a single lens, as shown in Fig. 3. A tuning range of 1 nm was achieved and bandwidth narrowing from 4 nm to 0.2 nm. Although bandwidth narrowing have been reported by others, the addition of wavelength tuning with a self-aligned cavity has, to the author's knowledge, not been reported before. Applications such as optical pumping of hyper polarized gases or Rubidium gas [12] will benefit from fine-tuning the center wavelength of the ECL. We anticipate that the concept can also be applied to arrays and stacks of high power laser diodes.

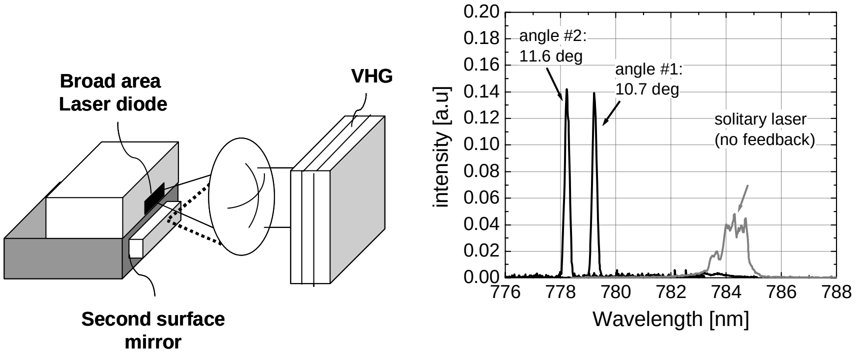


Fig. 3. Self-aligned ECL with high power multimode broad area laser

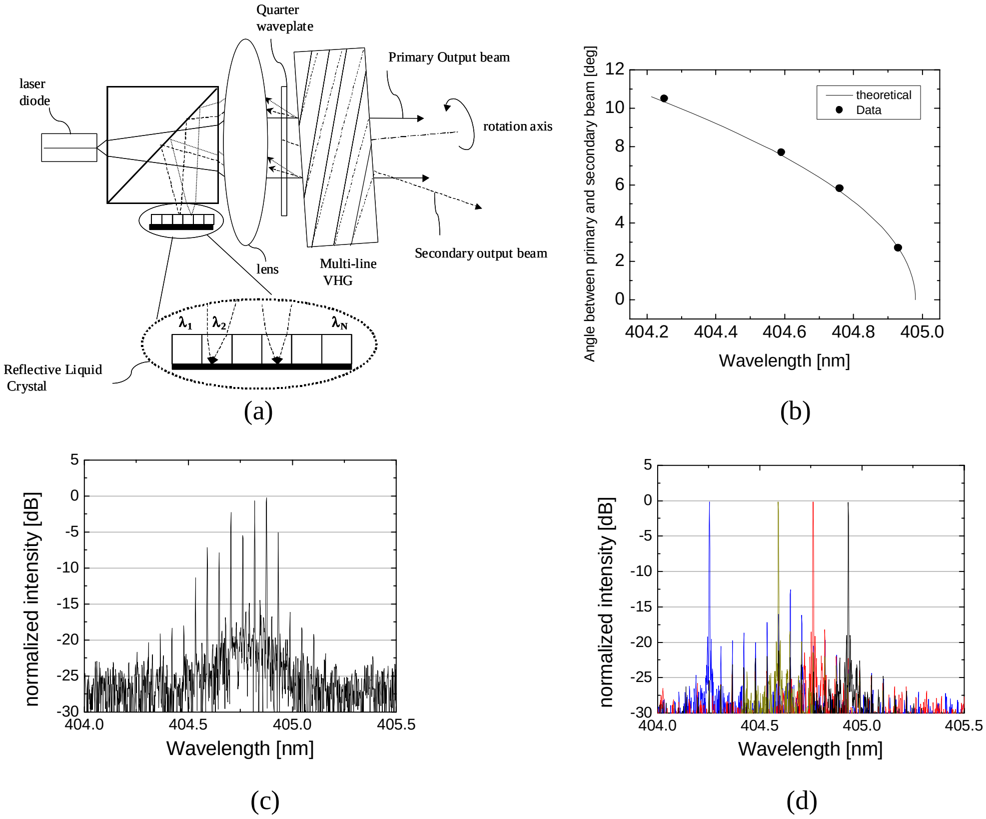
4. Fast, large tuning range, and passively aligned ECL

The tunable self-aligned ECL presented above has a tuning range limited by the numerical aperture of the collimated lens. In Fig.4(a), we show an architecture that increases the tuning range to several tenths 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.

To experimentally test the concept of this ECL architecture based on a polarizing beam-splitter, the following components are positioned according to Fig.4(a): a VHG with one grating wave-vector recorded (referred to as single line) with 40% efficiency and 4 mm length, a 4 mm focal length single element lens, a 3 x 3 mm polarizing beam-splitter, a quarter wave plate at 405 nm and a 2 x 2 mm mirror to simulate a reflective LC cell with no polarization rotation and an off-the-shelf 10 mW 405 nm laser diode. Fig.4(c) shows the spectral characteristic of the diode without feedback and Fig. 4(b,d) show, respectively, the tuning range and the single frequency mode spectrum when feedback is applied. 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%).



(a)

(b)

(c)

(d)

Fig. 4. (a) Extended wavelength tuning range self-aligned ECL based on multiplexed gratings and LCD tuning control. Experimental demonstration of the concept with a single line VHG and a reflective mirror in place of the LCD (b) angular wavelength tuning of the VHG in the plane of Fig. 4(a) (c) original diode spectrum (d) spectra of the ECL at different VHG angles.

6. Summary and conclusion

We have experimentally demonstrated a self-aligned tunable External Cavity Laser based on volume (thick) holographic reflection gratings. Tunable single frequency operation has been achieved at 405 nm and 785 nm over 1 nm. Tuning high power broad area lasers has also been demonstrated with a 1 nm spectral range and bandwidth narrowing from 4 nm to 0.2 nm.

The effective cavity length of the ECL is approximately twice the physical length of the ECL by construction. Because the resulting linewidth of the ECL is inversely proportional to the square of the cavity length [14], the linewidth is decreased by a factor four compared with an ECL of similar physical length.

A concept for extending the tuning range is presented and preliminary experimental results suggest that the tuning range can be increased to several tens of nanometers. We plan to pursue a demonstration of the extended tuning range in future work.

We would like to thank John Hall and Ron Logan for their valuable insights on the self-aligned laser cavity.