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External-cavity lasers based on a volume holographic grating at normal incidence for spectroscopy in the visible range

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ABSTRACT

We present two external-cavity diode lasers that utilize a volume holographic grating as the frequency selective feedback element. By using the grating at normal incidence, it is possible to design simple and compact external-cavity diode lasers that have sufficient tunability for molecular spectroscopy. The first design utilizes a long-cavity designed for narrow linewidth and good long-term stability. The laser operates near 635 nm and it has a PZT-controlled tuning range of 28 GHz and a 1-s linewidth of 900 kHz. The second design utilizes a grating attached very close to the laser diode, making the laser compact, robust and easy to operate. The short external-cavity laser operates near 658 nm and it has a linewidth of 30 MHz. Continuous and mode-hop free tuning range of 145 GHz can be obtained by using a simple temperature tuning method.

1. Introduction

Compared to most other lasers, diode lasers are simple to use, inexpensive and small in size. They have become fundamental tools in many fields of optical technology and experimental physics [1], such as optical communications, spectroscopy, and atom optics. In these applications, single longitudinal mode operation, narrow linewidth, broad tuning range and low drifts are generally favorable characteristics. Often these characteristics cannot be met with solitary laser diodes that tend to have broad linewidth, poor frequency stability and limited tuning characteristics. A common technique to improve diode laser properties is to expose the laser to strong and controlled optical feedback from an external reflector. By using external feedback it is possible to increase the laser cavity length and thus decrease the spectral linewidth by a factor of 100–1000 compared to that of a solitary diode laser. Side mode suppression ratio (SMSR) of 30–50 dB and accurate frequency tuning can be achieved by using a frequency selective feedback element, which is usually a diffraction grating in Littrow configuration [2,3] or more conveniently a partly transmitting grating in a similar configuration [4]. It is also possible to use separate optical elements for feedback and frequency selection, e.g., by having an interference filter in an external cavity formed by a mirror [5,6]. Such approach can help to reduce alignment sensitivity of the laser, however at the expense of increased complexity of mode-hop free frequency tuning.

A remaining challenge related to external-cavity diode lasers (ECDL) is to find a design that provides good frequency stability, accuracy and reproducibility without compromising the well-defined tuning characteristics. In general, these favorable properties can be achieved only if mechanical and thermal drifts of the laser cavity are carefully suppressed. Most of the reported ECDL geometries lead to a large mechanical structure, which makes the laser susceptible to mechanical vibrations and thermal gradients. To avoid these problems, we have designed a new external-cavity diode laser based on a compact volume holographic grating (VHG) [7].

While the focus of using the VHGs in laser applications has been in locking and narrowing the linewidth of high-power diode laser bars [8,9], their applicability to spectral narrowing of low-power diode lasers was demonstrated already over 20 years ago [10]. With the introduction of long-term stable holographic grating materials, the interest in VHG-based external-cavity diode lasers has recently re-emerged [7,11].

In this paper we demonstrate that the VHG technology is well suited for designing narrow-linewidth, long-term stable ECDLs that have large mode-hop free frequency tuning range. The basic principle of the laser cavity is schematically shown in Fig. 1a, and the detailed description and characterization of the laser are presented in Sections 2 and 3, respectively. We also discuss a

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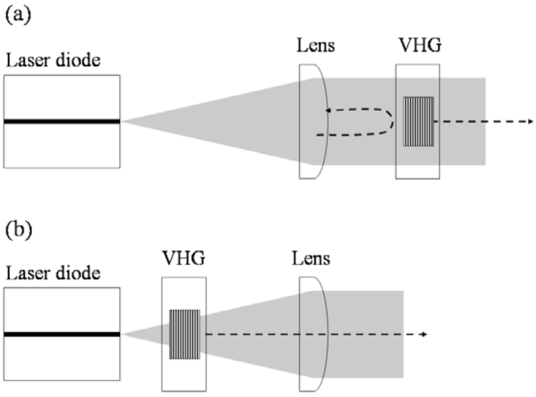

Fig. 1. Schematic drawings of the operation principles of the ECDLs. The volume holographic grating (VHG) provides strong feedback for the collimated beam in long-cavity design (a), while in short-cavity design (b), the VHG is placed at close proximity (few tens of micrometers) of the laser diode being able to provide feedback to only small portions of the diverging output beam. The short-cavity laser is compact enough to fit into a standard 9-mm TO-can.

previously introduced compact external-cavity laser in which the VHG is placed in close proximity of the laser diode facet [7]. This design is schematically depicted in Fig. 1b. The suitability of both ECDLs in molecular spectroscopy is demonstrated. The main results are summarized in Section 4, in which we also discuss the possible limitations of this approach.

2. Laser configuration

2.1. Volume holographic grating

Volume holographic gratings are Bragg reflectors that are fabricated by recording the interference pattern of two coherent light fields into a thick photosensitive media that maintains long-term stability of the recorded pattern. (For detailed description of VHGs and their long-term stability, see, e.g., Ref. [7].) The VHGs used in this work are fabricated in the bulk of a glass substrate. The resulting grating is thus protected from contamination and its optical surfaces can be cleaned with the same precautions as ordinary optics. When a light beam is directed into the VHG, it is reflected according to the Bragg condition,

$$\lambda = 2nD\cos(\theta), \tag{1}$$

where λ is the wavelength, n is the bulk refractive index of the VHG media, D is the grating period, and θ is the incidence angle relative to the grating normal. Note that VHG is not a dispersive grating – it simply reflects the light beam at the wavelength that satisfies the condition of Eq. (1). Unlike in the case of diffraction gratings, the wavelength selected by a VHG does not depend on the refractive index of the surrounding air at normal incidence. This feature can help to sustain good long-term stability of an ECDL when operating it in an environment where temperature, pressure, and composition of the laser cavity air may vary [12,13].

Normal incidence ($\theta = 0$) is a convenient choice when using a VHG as the frequency selective component of an ECDL. The laser diode output beam hitting the VHG is reflected directly back to the diode and no additional optical elements, such as mirrors, are needed in the external cavity. (A collimating lens is often used to maximize the beam volume that satisfies the Bragg condition, see Fig. 1.) The wavelength reflected back to the laser diode in the normal-incidence configuration is $\lambda = 2nD$. An advantage of this configuration is that the external cavity can be made simple and symmetrical relative to the optical axis. Symmetrical structure helps to reduce laser's sensitivity to external disturbances and to mechanical drifts [12]. In Section 3 we will also show that the normal-incidence configuration makes it possible to achieve large mode-hop free frequency tuning range with an ECDL.

One of the most important parameters of VHGs and diffraction gratings is their spectral resolution. Unlike in the case of diffraction gratings, whose resolution is inversely proportional to the beam diameter, the resolution of a VHG is inversely proportional to the interaction length L [14].

$$\Delta\lambda = \frac{\lambda^2}{\pi L} \tag{2}$$

In this work we have used two different VHGs, one designed for 635 nm center wavelength and the other one for 658 nm. Both VHGs have a physical length of 1.5 mm. The effective interaction length is slightly shorter corresponding to a nominal reflection bandwidth (FWHM) of 75 GHz, which is narrow enough to reliably suppress the characteristic longitudinal modes of the solitary diode laser. For comparison, the spectral resolution of the VHGs used in this work is similar to (or better than) that of a typical diffraction grating in the Littrow configuration, and approximately three times better than what can be obtained with narrow-band interference filters [6].

Another important parameter of the VHG is its peak reflectivity, which depends on the modulation depth of the VHG's refractive index pattern [7]. The VHGs can be fabricated with high absolute reflection efficiency, reaching 95% for a 1.5 mm thick VHG. The efficiency does not depend on the light polarization, which simplifies the ECDL design. (Diffraction efficiency of a typical diffraction grating depends on the light polarization and the laser diode orientation has to be adjusted accordingly. Sometimes an intracavity half-wave plate is needed to simultaneously optimize the diffraction efficiency and the diffraction bandwidth [12]). Reflectivity of the front facet of a typical laser diode is high, sometimes up to 30%, which means that a high reflection efficiency of the VHG is required to overcome the oscillations of the solitary laser. On the other hand, if a laser diode with an antireflection-coated front facet is used, a grating reflectivity of 15–25% is often sufficient to ensure reliable operation in a cavity mode determined by the grating. It is worth noting that usually it is not desirable to use grating reflectivity much higher than that required for stable ECDL operation, since high reflectivity compromises the ECDL output power (output beam is extracted through the VHG) and exposes the laser diode output facet to high intensities that can damage the diode.

Because the properties of a VHG, such as its peak reflectivity and reflection bandwidth, are independent of the other parameters of ECDL they can be tailored for a particular application more easily than those of diffraction gratings. For instance, the parameters can be optimized in order to achieve narrow linewidth operation of an ECDL [15]. The possibility of using a small laser beam is particularly interesting, since a small beam size makes the ECDL less sensitive to misalignment of the optical feedback element [5]. However, if the beam is very small, increased divergence reduces reflectivity, increases bandwidth, and can cause a slight deviation in the peak wavelength. Ultimate alignment stability can be obtained by applying a cat's eye configuration, where the feedback strength remains essentially constant for small misalignments of the feedback element. A drawback of the configuration is increased complexity that also makes it more difficult to achieve large mode-hop free frequency tuning. The cat's eye configuration has been previously used with interference filters [5,6] and a modified version of it has been recently demonstrated with VHGs [14].

In this work we have not used the cat's eye configuration but we have utilized the possibility for a small beam size otherwise: In addition to improving alignment stability, the small beam size can be used to reduce the physical length of the external cavity (since a collimating lens with a shorter focal length can be used).

Together with the fact that the VHGs can be made very small in size (e.g. 0.6×0.6 mm^2), this has allowed us to design a compact ECDL cavity that is easy to temperature stabilize. This design is discussed next.

2.2. Laser structure

In this section we give a detailed description of the ECDL that is schematically shown in Fig. 1a. To ensure good performance and small drifts, the laser cavity is designed to be robust, rigid and symmetrical with respect to the optical axis. All of the mechanical parts were made of aluminum. The exploded mechanical structure of the laser is presented in Fig. 2. The length of the structure is 68 mm including the $64 \times 64 \times 13$ mm^3 front and back plates. Above the bottom plate lays a 10-W Peltier element, which is used to control the temperature of the laser diode with 10-mK precision. The diode is mounted on a circular plate, which is screwed to the inner enclosure. The diode laser, which is not shown in Fig. 2, is a commercially available antireflection-coated InGaAlP device (SDL-7501-G1) with a nominal power and wavelength of 10 mW and 635 nm, respectively. A collimated beam is produced with an aspheric, antireflection coated lens (f = 4.5 mm, NA = 0.55, Thorlabs, C230TM-B).

The VHG (Ondax) is held in a separate mount comprised of three PZT-elements (Thorlabs, AE0203D04F). The antireflection-coated front facet (with residual reflectivity of $\ll$1%) of the laser diode allowed us to use a VHG with a rather modest reflectance of $\sim$35%. This was proved to be high enough to provide good laser stability and narrow linewidth, and yet low enough to avoid damaging of the laser diode. Since the output beam is transmitted through the VHG (whose input and output ends are parallel), the beam pointing is always parallel to the output beam of the laser diode, independent of the VHG angle. Moreover, as the VHG is oriented at normal incidence with respect to the collimated output beam, also the lateral shift of the beam position can be virtually neglected. For a 1.5 mm thick VHG made from glass (n = 1.45) the lateral displacement of the output beam as a function of VHG angle is $\sim$0.47 μm/mrad. In our design this effect is negligible since the tilting angle around normal incidence is limited to some tenths of a mrad.

An O-ring is set between the VHG structure and the inner enclosure to provide some level of hermeticity in the laser cavity and to be able to optimize the angle of the VHG by using three adjustment screws mounted trough the front plate. By using the three PZT-elements for fine tuning, it is possible to synchronize the cavity length tuning with the grating angle tuning in order to get a mode-hop free tuning range that is broader than the free spectral range of the cavity [16]. The optical length of the laser cavity, 15 mm, was selected so that it would be long enough to achieve a narrow linewidth (<1 MHz), while ensuring a large longitudinal mode spacing of $\sim$10 GHz, which helps to minimize the probability of cavity mode hops.

The entire laser structure is placed within an outer enclosure that is sandwiched between the end plates. The end plates are connected to each other with four invar rods (not shown in the figure). O-rings are used in between the enclosure and the end plates in order to obtain some level of hermeticity and also to provide a buffer to allow stress-free thermal expansion. The laser output beam is extracted through a window (not shown in the figure), which is antireflection coated and slightly tilted in order to avoid residual optical feedback to the laser. The use of the outer enclosure helps to reduce laser temperature fluctuations and damps the variations due to ambient pressure that could otherwise deform the sealed laser cavity and hence cause laser frequency deviations.

3. Performance

3.1. Long-cavity ECDL

Passive stability (no feedback loop) of the laser design described in Section 2.2 was determined by measuring both the short-term and long-term frequency stability. Low-noise electronics [17] were used for the laser current supply, for temperature control, and for the PZT control voltages throughout the measurements. To determine a practical 1-s linewidth, the laser frequency was recorded in the time domain with an oscilloscope using a Fabry–Perot interferometer (FPI) as the frequency discriminator. Fig. 3 shows the resulting 900 kHz linewidth with a Gaussian fit, indicating good short-term stability. Single-mode operation and good spectral purity of the laser were confirmed using the FPI and a grating spectrum analyzer (Ando 6315). The side-mode suppression ratio was measured to be better than 35 dB when operating the laser close to the center wavelength of the laser diode gain curve.

To determine the long-term stability of the free running laser, the laser frequency was tuned to the linear part of the slope of an iodine absorption line that was used as a frequency-to-amplitude converter. The laser beam passed a 20 cm iodine absorption cell three times, and the cell was at ambient temperature (20 °C)

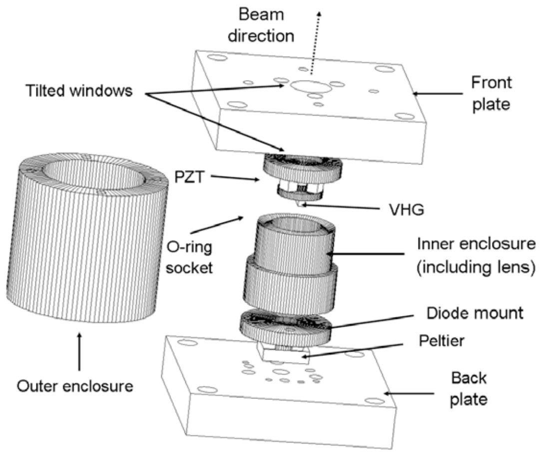

Fig. 2. Exploded view of the long-cavity ECDL structure. The laser diode, the two output windows and four invar rods are not shown in the figure. All the components are in scale.

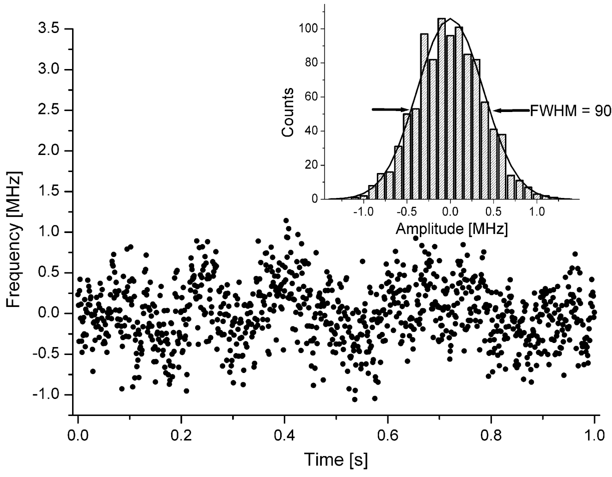

Fig. 3. Practical 1-s linewidth (inset) of the 635 nm ECDL calculated from the laser frequency fluctuations in the time domain including a Gaussian fit.

corresponding to a gas pressure of 30 Pa. Laser frequency, ambient pressure, power and temperature were recorded with 11 s intervals using 150 ms of averaging. An 8-hour measurement result is presented in Fig. 4 showing good passive long-term stability with the maximum deviation of the laser frequency being only 80 MHz. We performed several measurements where ambient pressure variations were in the order of 1 hPa, but no clear pressure dependency of the laser frequency was observed. The measurements were done in a temperature controlled room where the temperature remained stable within 0.1 °C around an average value of 20 °C. No temperature dependency of the laser frequency could be determined in these conditions. Such dependency can be, however, expected to small due to the temperature stabilization of the ECDL cavity. (The inner enclosure of the cavity is in good thermal contact with the laser diode mount that lays on a Peltier element, see Fig. 2. The end plates are connected to each other with invar rods that have small thermal expansion coefficient.)

Fig. 5 shows the measured frequency tuning range of the laser. The tuning was done by tilting the VHG with the three PZT elements, while the relative magnitudes of the voltage signals fed into the PZTs were empirically optimized for mode-hop free operation. The frequency scale was obtained with the FPI peaks and iodine transitions [18]. The continuous mode-hop free tuning range is ~28 GHz, which is almost three times the FSR of the external laser cavity. It is possible that the actual tuning range is even broader since the sweep was limited by the PZT-element displacements. To the best of our knowledge, this is the first demonstration that large mode-hop free tuning can be achieved also with VHGs by tilting the grating angle in a standard ECDL configuration. In principle the feedback would be lost immediately when the VHG is tilted, but in practise beam divergence ensures that there are some rays that satisfy the Bragg condition and that are reflected back to the laser diode when the VHG is slightly tilted.

Broader tuning range can be achieved by varying the drive current and the temperature of the laser. At the ambient temperature of 20 °C, the tuning slopes were −3 GHz/mA (0.004 nm/mA) and −9.3 GHz/K (0.0125 nm/K) for the drive current and temperature, respectively. A total tuning range of ~70 GHz was obtained by varying the temperature and current, which is in agreement with the 75 GHz bandwidth of the VHG. Because the bandwidth of the VHG is relatively small compared to the FSR of the solitary diode laser, the desired wavelength can be obtained with good reproducibility. With certain temperature and current settings, we obtained the same mode and thus the same wavelength every time. This was verified during the measurement period. Altogether, the reproducibility of the laser was observed to be better than, e.g., with the ECDL reported in [17] (which occasionally jumped to an adjacent mode of the laser diode).

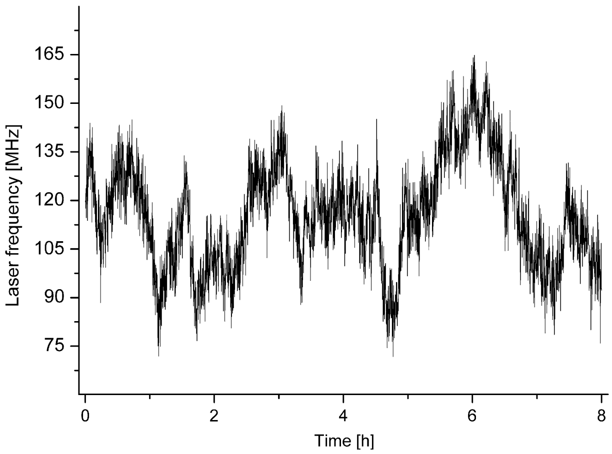

Fig. 4. Measured long-term frequency fluctuations of the free-running 635 nm ECDL. The data were recorded every 11 s using 150 ms averaging. (The noise appears large due to the short averaging time of each sample).

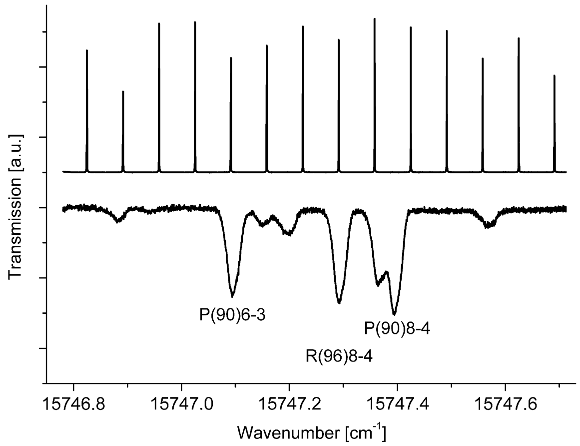

Fig. 5. Continuous and mode-hop free scan of 28 GHz of the long-cavity ECDL including Fabry–Perot interferometer (FSR = 2 GHz) peaks (above). The R(98)8-4 line of I2 absorption spectrum was used as frequency reference in the stability measurement reported in Fig. 4.

3.2. Short-cavity ECDL

The new ECDL described above in Sections 2.2 and 3.1 is designed especially for metrology and atomic physics. However, in gas detection applications, particularly in industry, larger modhop-free frequency scanning ranges are favorable. In such applications it is often desirable to have a laser design that is compact and simple to assemble and use. These requirements can be met with the short-cavity ECDL that is schematically shown in Fig. 1b. The laser consists of a laser diode (Sanyo DL-6147-040) with standard off-the shelf coating, estimated at 15%, that emits at 658 nm, and of a high efficiency VHG (~75%) that is attached a few tens micrometers to the diode. The laser equipped with the VHG fits into a standard 9-mm TO-can. Temperature of the can is controlled to within 10 mK using a Peltier element, and the output beam is collimated using an antireflection coated lens ($f = 4.5$ mm), which is placed after the VHG. Obviously, the fractional power reflected back to the laser diode by the VHG is smaller in this configuration than in the long-cavity ECDL, since the laser beam incident to the VHG is not collimated and hence only a small portion of the angularly spread output power satisfies the Bragg condition. The feedback is, however, strong enough to ensure reliable laser operation at the frequency determined by the VHG, and the side modes of the laser diode are suppressed by more than 35 dB. Due to the short external cavity the laser linewidth is not significantly narrowed compared to that of a typical single-mode diode laser. We measured a linewidth of ~30 MHz using a scanning FPI with a ~0.5 ms sweep over the laser line.

An advantage of the short external cavity is that the laser frequency can be tuned without mode hops over a large range simply by varying the laser temperature. This tuning method is demonstrated in Fig. 6, which shows an example of the measured Doppler broadened iodine spectrum [18], demonstrating a continuous and mode-hop free scan of ~145 GHz and suitability of the laser for gas detection applications. In addition to the iodine spectrum, an FPI was also used as a frequency marker to confirm the tuning range and to ensure that there are no mode hops during the scan. The observed mode-hop free tuning range is significantly larger than the reflection bandwidth of the VHG. This can be explained

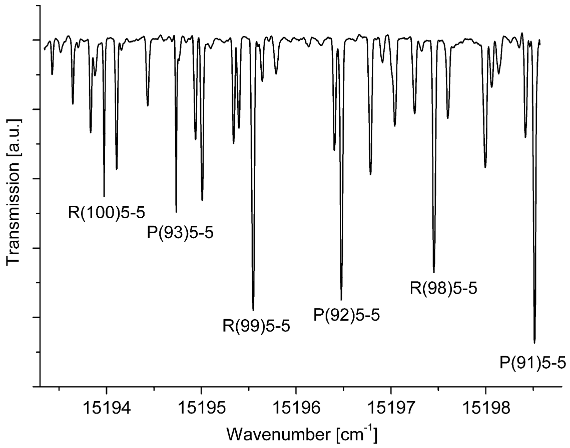

Fig. 6. Iodine spectrum as a function of laser frequency tuning for the short-cavity ECDL, demonstrating a continuous and mode-hop free scan of 145 GHz. Some of the iodine transitions are identified for clarity.

by the fact that the entire laser can, also the VHG, is kept at the same temperature; the temperature scan thus shifts not only the frequency of the laser cavity, but also that of the VHG. Both the laser diode and VHG frequencies have negative temperature coefficients so they tune to the same direction. The mode-hop free tuning range is the largest reported so far for a VHG-stabilized laser diode, and it is equivalent to that of typical DFB and DBR lasers. Since the DFB and DBR lasers are commercially available only for wavelengths longer than ~700 nm, the short-cavity VHG-based ECDL is an interesting choice for applications such as holography and gas detection especially in the visible.

4. Discussion and conclusions

We have presented a novel external-cavity diode laser that utilizes a volume holographic grating as the optical feedback element. The laser was designed for good passive frequency stability and it is insensitive to variations of ambient pressure. The laser has a 1-s linewidth of 900 kHz and it is hence well suited for high resolution spectroscopy. Continuous and mode-hop free tuning range of 28 GHz was achieved, demonstrating that synchronous tuning of the ECDL cavity length and grating angle works well also with VHGs despite their non-dispersive nature (as compared to diffraction gratings).

The new ECDL reported in this paper was designed particularly for applications in metrology and atom physics where a single atomic or molecular transition needs to be reliably addressed. For such applications, the demonstrated total tuning range, 70 GHz, of the laser frequency is sufficient. However, it is obvious that as such the design is not suitable for applications that require wide tuning of the laser wavelength. Although this limitation arises from the narrow reflectance bandwidth and non-dispersive nature of the VHGs, it can be overcome by different designs. So far two solutions to this tuning problem have been presented: One solution utilizes a VHG in a retroreflector configuration, in which one or more mirrors are needed in the ECDL cavity in addition to the VHG [14,19]. Another possibility is to use a chirped VHG, in which the grating period varies in a direction transversal to the laser beam, hence allowing laser wavelength tuning to be done by simply translating the VHG [20]. Both of these methods can provide wavelength tuning of >1 nm, at least [14,19,20].

A more simple way of extending the frequency tuning range, although at the expense of increased linewidth, is to attach the VHG in immediate proximity of the laser diode output facet. This short-cavity ECDL design makes it possible to keep the laser diode and VHG at the same temperature, hence allowing quasi-synchronous temperature tuning of their frequencies. We have shown that such temperature tuning method can provide continuous and mode-hop free frequency scans of 145 GHz. It is possible that even larger scans are possible with improved matching of the temperature tuning coefficients of the laser diode and VHG, although such possibility was not explicitly studied in this work. The small size, ease of use, and large continuous frequency tuning range make the short-cavity ECDL ideal for spectroscopic applications that require measurement of multiple molecular transitions simultaneously. The ECDLs reported in this work were designed to operate at 635 nm and 658 nm, but the same designs can be adapted to virtually any visible or near-infrared wavelength above 350 nm where diode lasers are available.

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