Compact Bragg Grating Stabilized Ridge Waveguide Laser Module With a Power of 380 mW at 780 nm

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Abstract—A single ridge waveguide laser wavelength stabilized by a compact external Bragg grating cavity with an output power as much as 380 mW and a beam quality factor $M^2$ of 1.3 is presented. A characterization concerning tunability by current, short-term optical linewidth, and intensity fluctuations is performed. The device exhibits a wavelength tuning factor at 780 nm of 0.5 pm/mA, a short-term optical linewidth of 18 kHz, and a low-frequency relative intensity noise of –136 dB/Hz. These characteristics allow a high resolution absorption spectroscopy of the D2 line of rubidium.

Index Terms—Semiconductor device packaging, Diode lasers, Laser stability, Bragg gratings.

EXTERNAL cavity diode lasers (ECDLs) operating in the near infra-red spectral range became a standard tool in the field of atomic physics as well as in bio-medical applications. This is due to a narrow linewidth [1], precise frequency selectability, high power in the order of 100 mW as well as the excellent side mode suppression of 50 dB and higher of ECDLs. They are applied for atom cooling and trapping [2], [3], high precision spectroscopy for establishing laser optical frequency standards [4], quantum information and Raman spectroscopy [5]. However, advanced applications require a narrow linewidth below 100 kHz as well as high output power on the several hundred mW regime [6]. Furthermore, applications of conventional ECDLs in Littrow [7] as well as in Littman/Metcalf [8] configuration suffer from their sensitivity on ambient conditions as there are vibrations, acoustics, and temperature variations. Approaches via Distributed Bragg Reflector (DBR) structures [9] as well as via Volume Holographic Gratings (VHGs) [10], [11] have been chosen for overcoming these issues of conventional ECDLs and Distributed Feedback (DFB) lasers [12].

VHGs consisting of photo-thermo-refractive glass with a high damage threshold, however, have proven to be able to simplify external-cavity configurations [13]. Placing a reflective VHG in front of the laser diode with the grating period perpendicular to the light propagation helps minimize the packaging size. This VHGBased external cavity design is a convenient means used to stabilize high-power arrays of broad area [14] or tapered [15] diode lasers. Such high power ECDLs have been applied for rubidium (Rb) laser pumping at 780 nm [16] and optical pumping of delta oxygen at 763.8 nm [17]. Regardless of the high output power of these diode laser arrays, they can hardly be used for high-precision manipulation of atoms and particles since they suffer from a broad spectral linewidth and a non-Gaussian, low-brightness beam profile with a poor spatial coherence.

In this document we investigate an easy-to-use, compactly packaged VHG stabilized single ridge waveguide laser with a nearly diffraction-limited output beam with an output power as much as 380 mW at an operating wavelength of 780 nm. We investigate the output power along with the wavelength characteristics with respect to a gain current sweep. Moreover, we determine the short-term optical linewidth in a beat measurement of two identical lasers. Finally we demonstrate the spectral purity with a high-precision Doppler-free absorption spectroscopy of Rb vapor.

The ECDL design in a TO39 packaging including a thermo-eletric-cooler (TEC), the laser chip, collimation lenses and a VHG is depicted in Fig. 1. The TO39 can has an overall length of 32 mm and a diameter of 10 mm. The employed laser diode chip is 3.9 mm long and soldered on an AlN heatsink. The device’s vertical structure consists of a GaAsP single quantum well active region surrounded by doped 800 nm Al$_0.4$Ga$_0.6$As waveguide layers, which are in turn wrapped by a Al$_0.85$Ga$_0.15$As cladding layer on top and a...
The laser diode is anti-reflection (AR) coated with a reflectivity profile obtained. The beam quality factor M2 has been respectively. As a result, an almost diffraction-limited beam is obtained with a residual reflectivity below 0.2 % at 780 nm. The VHG’s facets are covered by an AR coating via UV light exposure and afterwards thermally cured [18].

The VHG is centered around a wavelength of 780.0 nm, has a spectral bandwidth of 0.1 nm and directs a fraction of 12 % of the incoming intensity back to the laser diode. It consists of silicate glass doped with silver, flourine and cerium and has a length of 3 mm. The grating is inscribed holographically via UV light exposure and afterwards thermally cured [18]. According to the Bragg condition, the grating period is 260 nm [19]. The VHG’s facets are covered by an AR coating with a residual reflectivity below 0.2 % at 780 nm.

The absolute output power of the ECDL is recorded with the help of an optical power meter after the beam has passed through an optical isolator. The results are shown in Fig. 2. There, one can see that the insertion of the VHG leads to a decrease of the threshold current by 35 mA down to 78 mA. For currents higher than the threshold, the output power rises on average linearly with a slope efficiency of 0.8 W/A. A maximum of 380 mW was obtained at a current of 535 mA.

Fig. 2. Light-current characteristic of the ECDL: The total output power is recorded as the injection current is swept upwards. The inset a) depicts the optical spectrum recorded at a current of 400 mA. It shows that the laser operates in a single mode and the side mode suppression amounts to 50 dB. Inset b) depicts an extract from the sweep, in which the wavelength \( \lambda \) is recorded with a wavemeter. The laser head was stabilized to 15 °C.

The laser is run with an in-house developed current source. The laser head temperature is read via a thermistor, located closely to the TEC, and is controlled by an in-house PID controller. Without VHG the threshold current is 113 mA and the gain peak maximum is at a wavelength of 783 nm. For the laser at a current of 400 mA, the gain current is increased further, the TEC current reaches its limit of 1 A so that the system’s temperature can no longer be controlled. Consequently a gain current of 535 mA is the limit so far, but an improved heat transfer will help increase the output power in the near future.

The power slope in Fig. 2 exhibits small spikes and is slightly undulated. This behavior can be safely attributed to mode hops: Assuming the laser emits at a pair of longitudinal modes - one from the internal cavity, which is given by the chip itself, and one from the external cavity, which is bounded by the front facet of the diode and the middle of the VHG - the optical length of the laser diode is tuned when the current is swept. Thus the lasing modes of the internal and external cavity drift apart, which causes an undulation of the output power until another pair of modes becomes more resonant and a mode hop occurs [20].

The inset a) in Fig. 2 shows a characteristic optical spectrum for the laser at a current of 400 mA. It is evident that the laser operates in a single mode and the spontaneous emission is suppressed by 50 dB. In the current range above the lasing threshold this side mode suppression ratio (SMSR) remains nearly constant and only features deviations by a maximum of 1 dB. The grating period of 0.5 pm/mA illustrate the continuous tuning range. These slopes are interconnected by dotted lines indicating mode hops. The maximum mode-hop-free tuning range amounts to 10.5 pm which is 5.2 GHz.

All measurements of Fig. 2 are obtained at a laser head temperature of 15 °C to demonstrate the system’s performance at the rubidium D2 line. If, however, we shift the temperature upwards, the threshold current increases by 1.2 mA/K, whereas the slope efficiency remains constant. Consequently, the output power decreases regarding a fixed gain current value. Additionally, the grating period and thus the lasing wavelength can be tuned by temperature, too. The obtained tuning factor for the wavelength amounts to 10 pm/K. That means a tuning range of 0.2 nm above the rubidium absorption lines around 780.033 nm is accessible by tuning the laser head temperature to 35 °C. An evidence for temperature tuning can also be observed in the inset b) of Fig. 2. The lower edges of the parallel rising slopes are shifted by 6 pm/100 mA, which indicates a temperature difference of 0.6 °C between the TEC and the VHG in that current range. This is because the heat dissipation of the diode chip is asymmetric towards the TEC and the VHG due to different temperature gradients. Hence, a wavelength tuning via the gain current is supported by a tuning via temperature and thus extends the accessible wavelength range.

The power and spectral performance of our system is due to a combination of the long laser chip and a careful selection of the VHG peak reflectivity. A larger VHG reflectivity results in a lower output power and a stronger coupling between the internal and the external resonator and vice versa [21]. Consequently, we chose the VHG reflectivity with regard to output power maximization and a SMSR of at least 50 dB. With comparable VHG stabilized devices similar values of
Fig. 3. Experimentally obtained beat note of two identical VHG stabilized ECDLs at 780 nm and the corresponding Lorentzian fit. The 3 dB width amounts to 36 kHz. According to theory [22] the optical linewidth of one of the lasers is assumed to be half, i.e. 18 kHz.

We evaluate the short-term optical linewidth by the beat note of two identically constructed VHG stabilized ECDLs. Their beams are combined via a beam sampler and focused on a photodetector. The amplified photocurrent is evaluated with an electrical spectrum analyzer. The beat note and the corresponding Lorentzian fit are depicted in Fig. 3. The temperature of the laser heads is set to 15 °C and the gain currents are tuned to 216.5 mA and 218.6 mA, respectively, so that their wavelengths differ by 0.5 GHz and the power contribution of 137 mW of each laser is nearly equal. The sweep time is 1 ms/2 MHz. According to [22] the power spectrum of the resulting photocurrent is supposed to fit a Lorentzian shape with a full width at half maximum (FWHM) that equals the sum of the optical linewidths of each laser. Assuming them to be identical, the linewidth of each laser can be derived by dividing the FWHM by two. A Lorentzian fit is performed to the data resulting in a FWHM of 36 kHz with a standard error of ±1 kHz and thus a short-term linewidth of 18 kHz.

In order to confirm the performance of the narrow linewidth and the wavelength tuning range a Doppler-free saturation spectroscopy on Rb vapor is performed. The experimental setup is shown in Fig. 4. The ECDL is operated at an offset current of 210 mA. Additionally, an AC current with an amplitude of 10 mA and a frequency of 1 kHz is applied. Thus the emission wavelength is continuously tuned by about 5.2 GHz. The diameter of the output beam is first enlarged with a telescope to 1 cm. In this way a large volume of the Rb vapor is pumped. The same beam functions as the probe beam after it has been reflected back and is rotated in polarization by 90°. The transmission signal, now vertically polarized, is led to a photodetector by a polarizing beam sampler and is shown in Fig. 5. Three broad absorption dips can be seen, which belong to the transitions with the following ground states: $^{87}\text{Rb} \, 5S_1 \, F_g = 2$, $^{85}\text{Rb} \, 5S_1 \, F_g = 3$ and $^{85}\text{Rb} \, 5S_{1/2} \, F_g = 2$ [26], [27]. Most importantly, the hyperfine structure Lamb dips can be observed within these three absorption peaks. To confirm this, a high resolution zoom to the dips belonging to the transitions with the ground state $^{85}\text{Rb} \, 5S_{1/2} \, F_g = 3$ is depicted in the inset of Fig. 5. As a result of the narrow linewidth of our system these dips, which have a typical width in the range of the natural linewidth of Rb (6.07 MHz [27]), are clearly visible.

Since this saturation spectroscopy is usually done in direct detection instead of balanced detection a good signal to noise ratio, i.e. a low intensity noise of the laser, is essential. That is why we evaluate the relative intensity noise (RIN) for a frequency range from 50 Hz to 10 MHz where most microphonic resonances take place. We detect the laser signal with a photodiode and amplify the photocurrent with a...
transimpedance amplifier. Separated by a bias tee, the AC electrical signal is directed to an electrical spectrum analyzer while the DC power is monitored by a multimeter. The ratio of the AC electrical fluctuations and the DC electrical power, normalized to a resolution bandwidth of 1 Hz, results in the RIN. The obtained results for the laser operating at a current of 90 mA and a temperature of 15 °C are shown in Fig. 6. There, it can be seen that from a frequency of 1 kHz up to 10 MHz the RIN stays at a nearly constant value of −135 dB/Hz to −136 dB/Hz without any resonance spikes due to microphonic effects appearing. This result illustrates an upper limit of the RIN for gain currents higher than the threshold. For tuning the gain current to 150 mA makes the RIN drop by 15 dB. These results once more demonstrate the high mechanical stability of the presented design.

I. CONCLUSION

We have presented a very compact VHG stabilized external-cavity diode laser. Its output power exceeds the values previously measured for DBR lasers and devices stabilized by VHGs. Furthermore, concerning the narrow linewidth, our laser is an improvement compared with DFB structures and even portrays an alternative to bulky fiber lasers. In addition, our laser concept is very flexible concerning the VHG period and can be easily adapted to different wavelengths in the near infra-red. Along with the presented smooth and reproducible wavelength tunability at high output powers, it thus is an ideal candidate not only for the presented rubidium spectroscopy but also for Raman spectroscopy in mobile and portable operation.

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REFERENCES