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Frequency tuning of long-wavelength VCSELs

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Abstract

Tuning properties of long-wavelength VCSELs have been studied experimentally, for the first time to our knowledge. Injection current and temperature tuning rates of two VCSELs operating near 1512 and 1577 nm have been measured using a Fabry–Perot etalon with free spectral range 0.056 cm^{-1}. A 100-Hz saw-tooth modulation with depths of modulation of ∼10% or less was superimposed on a direct injection current (dc bias) to tune lasers in narrow spectral intervals (0.3–1.2 cm^{-1}) around a central frequency set by the dc bias. The lasers have been found to be capable of being tuned faster at higher levels of dc bias. The enhancement factors were up to ∼2 and ∼3 for the 1512- and 1577-nm lasers, respectively, as compared with their tuning rates measured at the levels of the dc bias close to the threshold of lasing. A linear dependence between injection current tuning rates and the levels of dc bias has been observed. Temperature tuning coefficients have been proved to be independent of the laser heat sink temperature and of the dc bias. Frequency tuning curves were approximated with a second-order polynomial. The frequencies of more than 40 absorption lines of CO, CO_2, H_2O and NH_3 known from spectral databases were compared with the calculated frequencies. The accuracy of the approximation was found to be within 0.2 cm^{-1} for spectral intervals up to 38 cm^{-1}. The dependence of current tuning rates of the VCSELs on dc bias was shown to be taken into account for accurate analysis of absorption line profiles. The results obtained can be used for precise spectroscopic measurements with long-wavelength VCSELs.

Keywords: Absorption spectroscopy; VCSEL; Frequency tuning; Spectroscopic measurements

1. Introduction

Recent advances in long-wavelength VCSEL technology have allowed the development of single-mode lasers with wavelengths covering the spectral interval between 1.3 and 2 μm [1], an important interval for open-path gas sensing applications. The most obvious advantage for applications in absorption spectroscopy offered by VCSELs is their capability of being tuned over wide spectral intervals without mode hops. Multi-species gas analysis [2,3], gas concentration measurements at high pressures [4], precise temperature measurements using absorption spectroscopy [5] and some other applications of VCSELs are based on their wide frequency tuning capabilities.

Our previous experiments with long-wavelength VCSELs [3,6,7] have demonstrated a remarkably good stability and reproducibility of the output frequency as well as their capability of resolving Doppler-broadened spectral features [3,8]. This combination of parameters makes long-wavelength VCSELs attractive for applications in high-resolution absorption spectroscopy. Tuning VCSELs over a relatively wide spectral range, however, results in non-linear dependence of their frequency on injection current [2,7–9]. A computer code was used by authors [2] to take into account non-linear frequency tuning of VCSELs operating near 770 nm and used for precise gas concentration measurements. Non-linear frequency tuning of a long-wavelength VCSEL operating near 1537 nm is also clearly seen from the etalon fringes reported in [8]. Little information is available about the details of emission spectra of long-wavelength VCSELs as a function of injection current [1,7]. In this paper we report the results of experimental studies of tuning properties of long-wavelength VCSELs important for their practical applications in high-resolution absorption spectroscopy.

2. Experimental design and characterization of long-wavelength VCSELs

We studied output parameters of two long-wavelength VCSELs (VERTILAS GmbH, Germany) operating near

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1512 nm (model VL-1512) and 1577 nm (model VL-1577) using our experimental set-up described in previous publications [3,6]. Each laser was packed in windowless TO-46 can and placed in a thermo-electrically cooled laser mount (Thorlabs, model TCLD-M9) supplied with a holder for a collimating lens. A TED-350 bench-top module and laser diode driver LDC200-VCSEL (both Thorlabs) allowed us to control the heat sink temperature and dc injection current of the laser placed in the mount with a precision of 0.01 °C and 1 μA, respectively. A function generator (SRS, model DS345) provided a saw-tooth modulation current superimposed upon a dc injection current via the laser diode driver.

We used an anti-reflection coated aspheric lens (reflectivity < 0.2% near 1.5 μm) to collimate the output of both lasers. The focal length and numerical aperture of the lens were 4.5 mm and 0.6, respectively. No realignment of the lens was required after replacing one laser with another in the mount. The lens was proved to produce no measurable optical feedback to the lasers. A power meter with resolution of 1 μW (Ophir Optronics, model PD300) could be introduced in the optical scheme for periodical control of laser output power. The collimated laser beam directed through a 1.9-m absorption cell with Brewster windows was focused onto a 1-mm InGaAs photodetector (Thorlabs, model PDA 400). To access water vapor absorption lines in ambient air, a 5.8-m open path in the laboratory was arranged using two flat mirrors. The signal from the photodetector was monitored with a fast oscilloscope (Tektronix, 300 MHz, model TDS-3032B) and digitized with a 12-bit analog-to-digital (AD) converter (National Instruments, model PCI-MIO-16E, 1.2 Ms/s) plugged into a personal computer. Synchronizing pulses from the function generator triggered the oscilloscope and AD converter. The signal processing and analysis were performed using LabVIEW 7.0 software (National Instruments). The experimental set-up was assembled on a research series optical table (Newport Instruments, model RPR-48-8). All experiments were performed at room temperature.

In our previous experiments we used CO and CO_2 absorption lines as frequency marks to study tuning parameters of laser VL-1577 [7]. This simple and reliable method allowed us to avoid the effects of optical feedback to lasers caused by Fabry–Perot etalons. The disadvantage of the method is a relatively low spectral resolution limited by a distance between gas absorption lines. Fabry–Perot interferometers could provide much higher spectral resolution, if the optical feedback effects are avoided. We observed the etalon patterns without optical feedback effects when the etalons were placed at a distance of ∼2 m from the laser and titled at the angle of about 5° with respect to the optical axis. In this study we used a thick uncoated optical plate (reflectivity of ∼4% for each surface) as a Fabry–Perot etalon with free spectral range 0.056 cm^{-1}. The absorption lines of gas mixture $CO:CO_2 = 1:1$ with known frequencies [10] were used with laser VL-1577 to measure the free spectral range of the titled Fabry–Perot etalon and to obtain absolute frequency marks in the tuning range of the laser. The absorption lines of water vapor and ammonia in the tuning range of laser VL-1512 were identified with the help of HITRAN [10] and Pacific Northwest National Laboratory [11] databases, respectively.

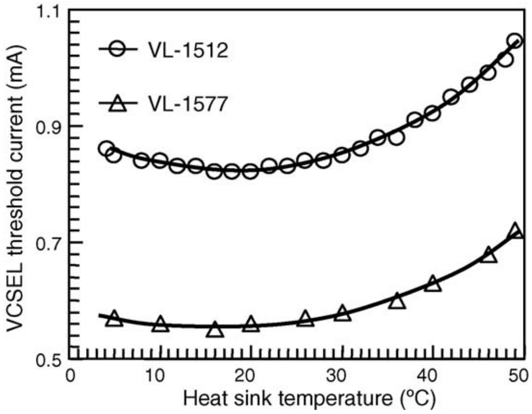

Fig. 1. The threshold injection current of the VCSELs as a function of heat sink temperature.

A 100-Hz saw-tooth injection current with depths of modulation of ∼10% or less was superimposed on a direct injection current (dc bias) to tune lasers in narrow spectral intervals (0.3–1.2 cm^{-1}) around a central frequency set by the dc bias. Fig. 1 shows the threshold currents of the VCSELs in dependence on heat sink temperature. The temperature dependence of the threshold currents appeared to be similar for these lasers.

The power of laser emission plotted against the injection current to threshold ratio is shown in Fig. 2. The saturation of laser output power with decreasing injection current and the roll off of the power at high substrate temperatures are observed for both lasers. Laser VL-1512 (Fig. 2a) allows for lower elevations of the injection current above threshold (up to ∼8) than VL-1577 (up to ∼12; Fig. 2a) because of higher values of its threshold current (0.87 mA against 0.55 mA for VL-1577 at 25 °C), while the upper limits of injection currents recommended by the manufacturer are almost the same for both lasers (7.0 mA for VL-1512 and 6.5 mA for VL-1577).

Fig. 3 illustrates non-linear frequency tuning of the VL-1577 laser. Fig. 3a presents fringes obtained with a Fabry–Perot etalon with free spectral range of 0.5 cm^{-1}. Linear saw-tooth ramps of different amplitudes were superimposed on the same 3.0-mA dc bias. As one can see from Fig. 3a, there is a substantial difference in tuning rates at the beginning and at the end of the frequency scans. The difference is more pronounced when the peak-to-peak amplitude of the linear ramp is increased from 1.8 up to 5.5 mA. Previous measurements made on VCSELs operating near 767 and 770 nm indicated the same evolution of etalon structures taken with a 1.3-kHz saw-tooth modulation current [2]. A LabVIEW-based computer code was developed in [9] to characterize non-linear tuning behavior of the VCSELs and to compensate the results of gas concentration measurements performed with the VCSELs for the non-linearity.

Fig. 3b shows patterns produced by the etalon with a free spectral range of 0.056 cm^{-1} on the same laser at the levels of dc bias varied in the range between 1.9 and 6.0 mA. A 100-Hz linear ramp with peak-to-peak amplitude of ∼0.4 mA was superimposed on the dc bias. As one can see from Fig. 3b, the modulation amplitude that we have chosen produces a linear frequency scan around a central frequency defined by the dc bias.