Wavelength modulation spectroscopy with a widely tunable InP-based 2.3 μm vertical-cavity surface-emitting laser

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We report on the successful application of recently developed 2.3 μm InP-based vertical-cavity surface-emitting lasers with a buried tunnel junction in a wavelength modulation spectroscopy measurement for carbon monoxide (CO) detection. The electrically pumped devices operate at room temperature under cw operation with stable single-mode emission and should allow for parts in 10^6 (ppm) level resolution measurement of CO with a standard optical setup. © 2008 Optical Society of America

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For several years now, long-wavelength ($\lambda > 1.3\ \mu$m) vertical-cavity surface-emitting lasers (VCSELs) are available and have been successfully employed in tunable diode laser spectroscopy (TDLS). TDLS has excellent properties for gas sensing, such as long-term stability, inherent self-monitoring, and maximum selectivity/very low cross sensitivity to other gases. These properties predestine this method for a range of applications where highest reliability is demanded, e.g., in aviation and health care. For compact and low-cost gas sensing applications, VCSELs have to be electrically pumped, single-mode, cw and at room-temperature operating devices. Such devices are already commercially available up to $\lambda = 2.04\ \mu$m. In almost all relevant technical data—except output power—VCSELs are superior to distributed feedback lasers. They exhibit reduced power consumption, higher FM modulation capability, an overall larger wavelength tuning range, and lower manufacturing cost owing to a less complex manufacturing process and the on-wafer testing option. Using wavelength modulation spectroscopy (WMS) in combination with VCSEL technology, many important gases are detectable in the near infrared: oxygen (O_2), water vapor (H_2O), hydrogen fluoride (HF), hydrogen chloride (HCl), methane (CH_4), ammonia (NH_3), and carbon dioxide (CO_2). All these gases—except O_2—are detectable at parts in 10^6 (ppm) or sub-ppm resolution with an optical path length of several tens of cm and an integration time of 1 s. However, both the number of gases and the sensitivity can be significantly improved by spectroscopy at higher wavelength, since the absorption strength of many gases increases significantly with the wavelength. The output power of typical VCSELs is of the order of 1 mW, while distributed feedback lasers easily achieve several tens of milliwatts. Assuming a laser relative intensity noise of -130 dB/Hz, the laser noise is equal to the shot noise of the detector at 3 μA photocurrent, which corresponds to an incident power of approximately 3 μW. If the laser noise is not compensated by special means, it cannot be lowered by an increase of laser power, so an emission power of the order of 1 mW is sufficient for WMS applications without excessive optical losses.

Recently, it was possible to extend the wavelength range of InP-based VCSELs up to 2.3 μm [1] using an optimized quantum-well design [2]. This is of great practical importance because these lasers allow for carbon monoxide (CO) measurements with VCSELs in the ppm range with path lengths of a few tens of centimeters. It is a significant advantage to measure CO without the need for edge emitter laser technology and/or the employment of expensive multipass cells [3]. While a wavelength of 2.3 μm marks the upper limit for the mature and reliable InP technology, it is easily accessible with GaSb-based active regions. Recently, realizations of GaSb VCSELs with both single-mode [4] and multimode [5] emission at 2.3 μm at room temperature were successful.

As shown in Fig. 1, the 2.3 μm VCSEL and the InAs photodetector were mounted side by side, whereas a spherical mirror was used to reflect the laser light onto the photodetector. The optical path length is about 40 cm. The VCSEL is mounted on a

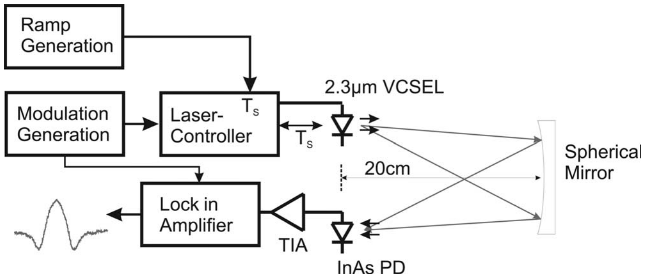

Fig. 1. Measurement setup. The spectrum scan was realized by a $T_0 = 4$ s scan of the laser's heat-sink temperature T_S, while a $f = 10$ kHz current modulation together with a lock-in amplifier was used to perform second-harmonic detection. PD, photodiode.

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thermoelectric cooler in a standard TO-5 housing without window.

A slow wavelength scan ($T_0 = 4$ s) was realized with temperature tuning, while a 10 kHz wavelength modulation was superimposed via injection current with a bias of 10 mA. The temperature scan was used to operate the laser at a constant bias current so that during the wide spectrum scan an output power is obtained that is comparable to the one in a sensor application. In a sensor application usually the bias current is specified first, and then the laser's heat-sink temperature T_S is adjusted so that the emitted wavelength matches the designated absorption line. A lock-in amplifier was used to perform standard second-harmonic detection. The lower limit of the temperature tuning was set to 15 °C to avoid condensation on the laser chip, although it is expected that the laser also works very well for lower temperatures. For higher temperatures the signal intensity decreases because of the decreasing laser output power (Fig. 2).

For a curve fit to several absorption lines in a broad wavelength range, a varying background can be a problem. Therefore, the background is usually measured without absorbing gas in the measurement cell and subtracted from the measurement curves. Here the standard Lorentzian lineshape model [6] with line parameters from the HITRAN database [7] was used for the curve fit model. Absorption lines of gases at ambient pressure and temperature usually have a Lorentzian shape. To obtain the second-harmonic spectrum, the output of the lock-in amplifier was divided by both the dc signal (Fig. 2) and the gain of the lock-in amplifier. This gives a normalized second-harmonic spectrum and a curve fit with model parameters from the HITRAN database directly yields concentration values without any need for further calibration. If only a single absorption line has to be fitted, the background can be assumed to be an offset or linear and can be included in the Lorentzian lineshape model, as shown in Fig. 3. The period length of the relatively strong fringes corresponds to an etalon length of $l \approx 2$ mm and is thus due to the window of the photodetector. It can be significantly lowered by using an improved window or a windowless detector.

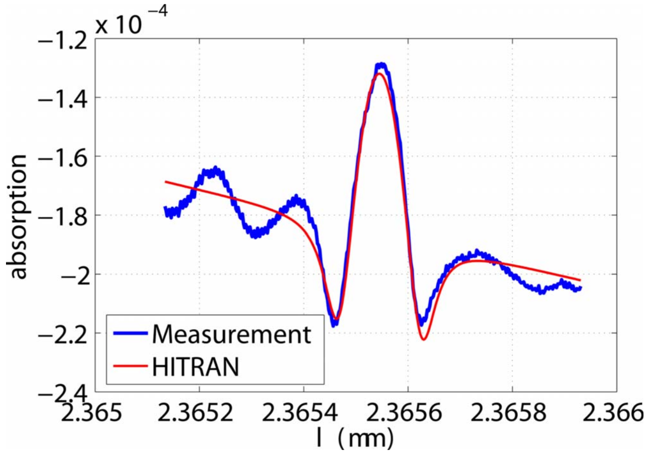

Fig. 3. (Color online) Second-harmonic spectrum of a single CO absorption line. The background was not subtracted but assumed to be linear and included in the curve fit model. The high fringe level is due to the window of the photodetector. The concentration is $C_{CO} = 11$ ppm. Absorption path length: 40 cm.

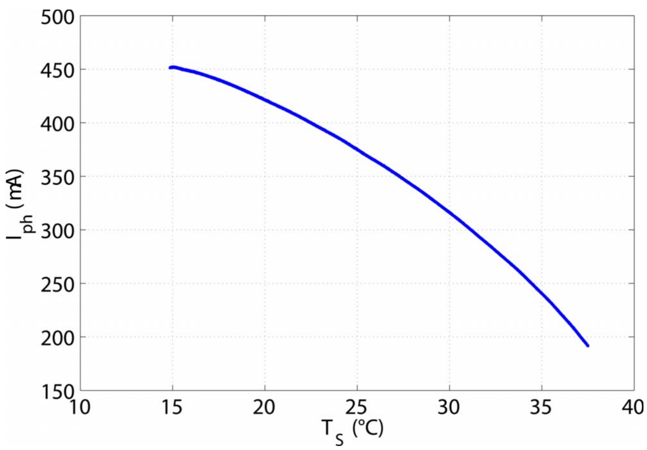

Fig. 2. (Color online) Photocurrent I_{ph} for different heat-sink temperatures T_S. The lower limit of 15 °C was to avoid condensation on the windowless laser.

The measurement of the whole spectrum shows good agreement with the HITRAN data as shown in Fig. 4, whereas the wavelength scale of H_2O seems to have an offset of about 0.03 nm to the CO and CH_4 wavelength scale. During the measurements, the laser remained in stable single-mode operation; artifacts due to multimode wavelength emission were not observed. The temperature to wavelength tuning coeficient of this laser was determined to be 0.174 nm/K.

In this Letter it is shown that the proven InP-based BTJ-VCSELs technology is also suited for gas sensing above 2 μm. Lasers at 2.3 μm wavelength are particularly important for CO sensing applications, since CO absorption lines below this wavelength do not yield necessary ppm resolutions with moderate technical effort. The availability of 2.3 μm

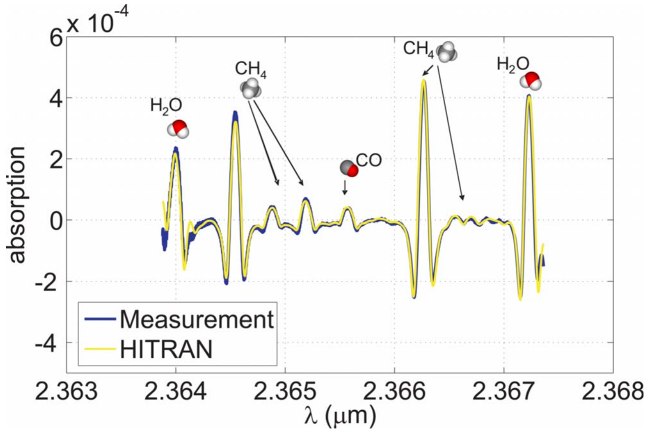

Fig. 4. (Color online) Second-harmonic spectrum measured with a temperature scan of the InP-based 2.3 μm VCSEL. The background was measured separately and subtracted from the shown curve. The concentrations are $C_{H_2O} = 1.1$ vol %, $C_{CH_4} = 80$ ppm, and $C_{CO} = 9.5$ ppm. Absorption path length: 40 cm.

InP- and GaSb-based VCSELs marks a very important technological step for gas sensing applications with high reliability. A WMS gas sensing application of the 2.3 μm InP lasers showed excellent performance. Extrapolating the results, it allows for CO absorption line measurements with ppm resolution.

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