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CO, CH_4 detection with 2.3 μm GaSb-based single-mode VCSELs

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Application of recently realized GaSb-based single mode vertical-cavity surface-emitting lasers (VCSELs) for gas-sensing at 2.3 μm is reported. Using a few ten cm optical path, carbon monoxide and methane were detected simultaneously in ppm range using wavelength modulation spectroscopy with laboratory equipments. The laser device showed stable single frequency operation during wavelength tuning by current and temperature. Influences of the laser PI characteristics for sensor application and data processing concepts for improving the gas-sensing performance are discussed.

OCIS codes: 140.7260, 300.6260, 300.6340

1. Introduction

Long term stability, inherent self monitoring, sensitivity and in-situ measurement[1] are the most favorable properties of tunable diode laser spectroscopy (TDLS) for gas sensing. In comparison to edge-emitting lasers, vertical-cavity surface-emitting lasers (VCSELs) have several significant advantages for TDLS like longitudinal single mode operation, low power consumption and efficient electrothermal wavelength tuning behavior [2]. Electrically pumped (EP) devices, which can be operated continuous wave (CW) at room temperature (RT), are particularly suitable for compact and low-cost applications. GaAs- and InP-based RT-CW-VCSELs covering a wavelength range from 700 nm to 2.3 μm are well known [3, 4, 5]. Recently, single mode EP-CW-RT VCSELs based on GaSb emitting around 2.3 μm have also been reported [6, 7].

The absorption for most gases such as methane and water is by more than one order of magnitude stronger at wavelengths above 2 μm than at shorter wavelengths [8]. Especially for carbon monoxide (CO), only the utilization of wavelengths around 2.3 μm (2ν band) enables sensing with the usually required ppm resolutions applying a few ten cm path length and one second averaging time for a typical sensor system using TDLS [9]. Due to its toxicity, CO affects the human health. CO escaping from home burners is the most frequent cause for unintentional death at home with a death toll of annually 500 persons in the USA [10]. Moreover, it is the most prominent gas to be detected for gas sensor based fire detection.

For long wavelength VCSELs (> 2 μm), the GaSb material system is the preferable candidate because of the small band gap energy and large optical gain in this spectral region, whereas the newly developed highly strained InP-based VCSELs at 2.3 μm have reached the upper wavelength limit of the InP material system [5]. For these reasons, GaSb-based VCSELs have a great potential to significantly extend the application areas of TDLS.

CO sensing with 2.3 μm GaSb-based edge-emitting Fabry-Perot lasers has been already reported with the employment of a 100 m multipass cell [11] or using 13 m absorption open optical path [12]. Combustion analysis of CO with 2.3 μm Fabry-Perot lasers [13] as well as distributed feedback (DFB) laser diodes [14] were also carried out. We present in this paper the first sensing results with a 2.3 μm GaSb-based VCSEL with a 2×20 cm open-path configuration under laboratory condition. We show that using wavelength modulation spectroscopy (WMS) [15, 16, 17] already these early CW EP GaSb-based single mode VCSELs enable simultaneous sensing of CH_4 and CO in ppm range applying a few ten cm path length and 1 Hz bandwidth with background subtraction.

During sensor operation in the field, where permanent background measurement and subtraction is not available, a resolution of CO detection of at least 17 ppm m (peak to peak) with one second averaging is expected. The laser background, which is the limitation of the sensitivity, cannot be subtracted initially because no data on long term stability is available up to now.

2. Experimental Setup

Here we present a rather simple open-path configuration to measure the CO concentration under laboratory conditions using WMS (Fig. 1). WMS is a gas-sensing method approved to be robust to 1/f noise distortion and to DC light background. The heat sink temperature T_S is

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ramped for scanning a wide wavelength range. This slow temperature scan covers about 6 nm wavelength within 4 seconds with a heat sink temperature variation from 15 °C to 40 °C. Since the laser is mounted on a TO-header without cap, the lower temperature limit is chosen to avoid condensation of humidity on the laser chip. At the same time a $f = 10$ kHz sinusiodal small-signal modulation of the laser current I_L is performed to generate the WMS absorption signals. The current bias is set to $I_0 = 7$ mA, while the threshold current of the laser is about 3.5 mA. The output power of the VCSEL is several ten μW at room temperature and the photocurrent decreases from 5 μA to 1.5 μA during the temperature scan of the laser diode because of the increasing threshold current. The second harmonic spectrum, which amplitude scales with the gas concentration, is detected with a lock-in amplifier. A spherical mirror is used to focus the light on the detector and to extend the path length to 40 cm. Assuming a laser RIN noise of -130 dB/Hz, the laser noise is here at the same magnitude with the shot noise, both dominating the Johnson noise of the preamplifier with a gain of 10^5 V/A. With increasing VCSEL output power the laser noise will be dominating and the total signal to noise ratio will be nearly independent of the photo current. Moreover, if the laser output power is improved during the ongoing development of the GaSb VCSEL devices, the spherical mirror can be replaced by a diffuse mirror to further simplify the setup and eliminate optical interference phenomena which can affect the measurement.

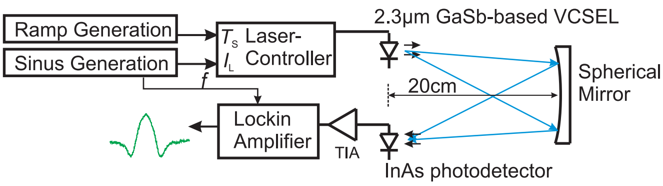
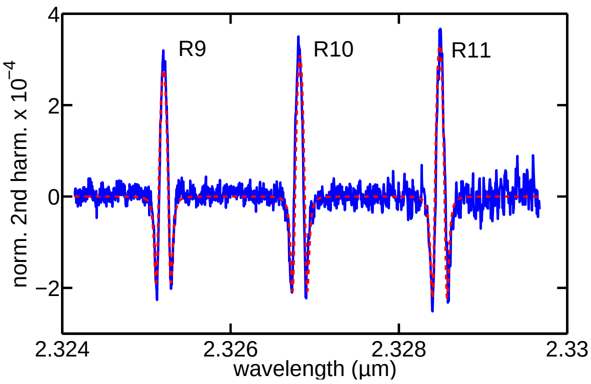


Fig. 1. Experimental setup for CO, CH_4 measurement under laboratory conditions. TIA: Transimpedance amplifier

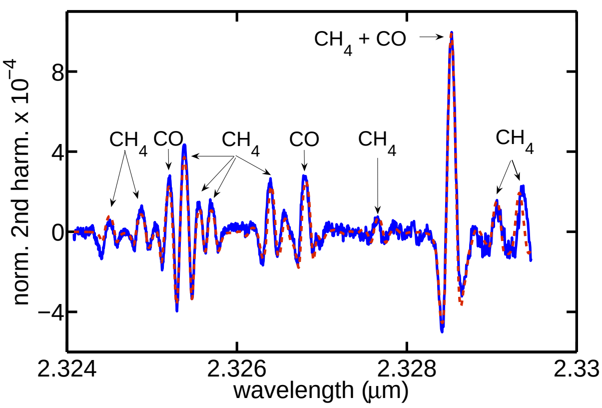
3. Results of the laboratory measurement

In order to detect CO, we filled a gas chamber with N_2 and inserted a small amount of CO and CH_4 as well as CO only. The second harmonic measurements for CO (Fig. 2(a)) and mixture of CO and CH_4 (Fig. 2(b)) together with their curve fits are shown. The second harmonic spectra are normalized by the DC light to be independent of the absolute light intensity and the gain of the pre-amplifier. The curve fittings using parameters from the HITRAN database [8] show very good agreement with the measurement data. The Lorentz profile based second harmonic formula from Arndt [18] is used to program the model function for the minimal mean square error curve fit.

A complex background pattern has also been observed



(a)



(b)

Fig. 2. Measured second harmonic spectra (solid curves): (a) with 57 ppm CO (b) 50 ppm CO and 140 ppm CH_4 and the corresponding curve fits with tabulated line parameters (broken curves).

during the CO measurement (Fig. 3), which was measured separately by filling the gas cell with nitrogen and subtracted in the measurement to enable a good curve fit. After subtracting the background pattern we determined the noise level on the second harmonic spectrum and the corresponding CO resolution.

For one second averaging time a resolution and lower limit for detection of 1 ppm m CO can be expected extrapolating the system performance, which corresponds to an absorption of $3 \cdot 10^{-5}$ (standard deviation).

The temperature to wavelength tuning behavior of the laser diode is assumed to be linear for the curve fit. The tuning coefficient scales with the longer wavelength of the GaSb VCSELs and was determined to be 0.23 nm/K, which is 30% larger than the 0.17 nm/K for the 2.3μm InP devices [5].

4. Discussion on the sensor performance

In a typical compact sensor system, current bias I_0 is usually tuned to scan the wavelength whereas the heat

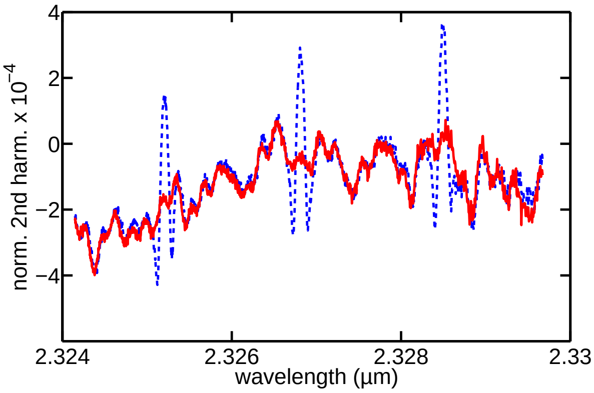


Fig. 3. Second harmonic spectrum (broken curve) and measured background (solid curve) with temperature scan.

sink is kept at constant temperature (T_s= const.). This is because wavelength tuning with current is significantly faster. The broad wavelength tuning range of at least 6 nm with a current tuning coefficient of approximately 1 nm/mA enables an automatic absorption line identification concept which could be implemented in the sensor.

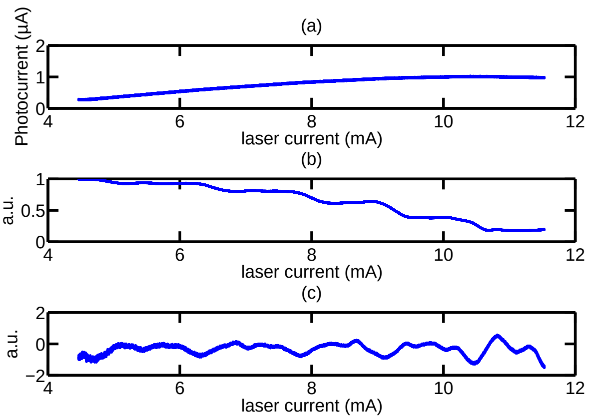


Fig. 4. The first harmonic measured without gas (b) (i.e. approximate derivative of PI characteristic) shows cascade behavior with increasing laser current, which indicates that the laser PI characteristic (a) exhibits kinks as well. This causes the complex background pattern on the second harmonic spectra(c).

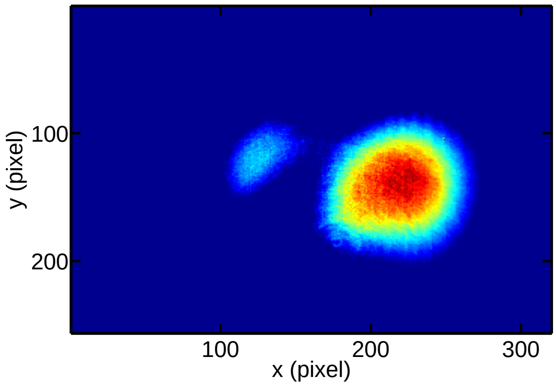
A complex background pattern exists in a current scan spectrum as well. While in a laboratory setup the background can be determined by a reference measurement near-time before sensor operation, this is not suitable for a mobile sensor system in the field. Due to the uncertain stability of the background pattern, repeated measurements including venting with non-absorbing gas or reference measurement using a second photo detector are required. To circumvent the necessity of reference measurements we investigated the device behavior at varying current because the background pattern in the second harmonic spectra can be attributed to features in the PI characteristic.

The measured harmonic spectra consist of two components: the harmonic gas spectra caused by the gas absorption, which are approximately the derivatives of the gas absorption spectrum at small wavelength modulation amplitudes [16, 19], and the derivatives of the PI characteristic. We measured the PI characteristic of the laser device and also the approximate first derivative of the PI characteristic by measuring the first harmonic without gas absorption, which is the background offset in the first harmonic spectra. It can be seen clearly that the first derivative shows steps (Fig. 4(a)), which corresponds to kinks in the PI characteristics (Fig. 4(b)). The second harmonic without gas absorption (Fig. 4(c)) indicates the second derivative of the PI characteristic and is the background for second harmonic gas spectra. For typical lasers the PI characteristic can be described as a polynom third order and the laser induced second harmonic background is typically a negative offset with a slight negative slope.

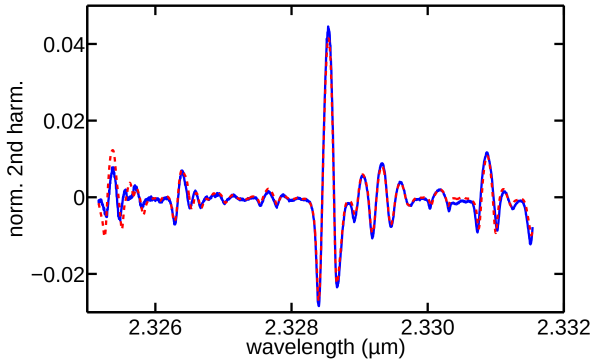
One assumption for the kinks in the PI characteristics is that the transversal mode rotates with the laser current and thus causes a change in light intensity at the photodetector. To investigate the behavior of transversal modes we measured the far-field of the laser diode with an InSb based infrared camera. A LP 01 transversal mode emission has been observed (Fig. 5 (a)). However, measurements of the far field for different injection currents showed no rotations. Another assumption are mode flips while tuning of the laser current. A successful curve fit to measured gas absorption spectra showed that no wavelength/mode flips are associated with the steps/kinks (Fig. 5 (b)). With mode flips, it would not be possible to fit the spectra because the wavelength scale changes discontinuously. The dynamic range/amplitude of the background pattern is different for the temperature scan ($5 \cdot 10^{-4}$) (Fig. 3) and the current scan (10^{-3}) (Fig. 6), which indicates that the complex background pattern is not caused by any optical resonance.

The background can not be simply measured once before and subtracted afterward during sensor operation because the reason for the kinks of the PI characteristics is still unknown and the long term stability of the background is uncertain. Signal processing methods like filtering are therefore the only possibility to reduce the background pattern during the sensor operation without adding complexity of the sensor.

The background pattern cannot be eliminated by averaging over time because it is not random. Nevertheless, the frequency components of the background pattern are concentrated at slightly lower frequencies compared to the gas absorption signal; therefore the background pattern can be also filtered with a high pass filter. Using a fast Fourier transform (FFT) filter the overall peak to peak amplitude of the background pattern could be re-



(a)



(b)

Fig. 5. Different measurements to investigate the reason of the kinks of the PI characteristics: (a)Measurement of the far field of the GaSb VCSEL with injection current of 11 mA (b) Measured CH_4 second harmonic spectra (wavelength is tuned by current) and the curve fit (broken curve).

duced from 10^{-3} to $2 \cdot 10^{-4}$ (Fig. 6). The performance of our system is therefore not limited by noise or interference but by the laser background. $2 \cdot 10^{-4}$ background distortion in the second harmonic spectrum corresponds to 14.7 ppm m distortion in the absorption curve, a factor three is taken into account because the amplitude of the second harmonic spectrum is about a third of the absorption with optimized modulation amplitude (Eq. (30) in [18]). One issue is that the signal amplitude will be also attenuated after the filtering by 15 %. The maximum error due to false absorption for the CO detection is then 17 ppm m, which represents the worst case. This corresponds to 42 ppm with 40 cm optical path length (2×20 cm folded optical path) and 0.1 s time resolution extrapolating our sensor performance. Improvement of the signal to noise/background pattern and therefore the resolution of CO detection can be achieved by using a curve fit with a proper model function for description of the exact form of the absorption lines. There is no performance improvement by increasing the integration time because of the laser background.

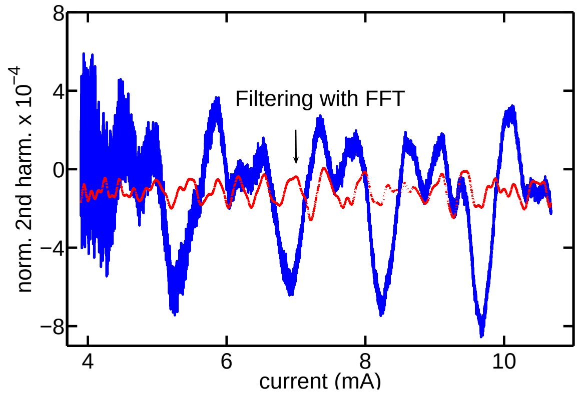


Fig. 6. Measured background pattern with current scan and the background pattern with FFT filtering

5. Conclusion

It has been shown in this paper that the newly developed CW EP GaSb-based VCSELs are well suited for simultaneous gas detection of CO and CH_4 at 2.3 μm despite low output power. Compared to the InP based VCSEL, the GaSb based VCSEL has a 30 % higher temperature tuning coefficient, lower threshold current and the GaSb material system is a suitable candidate for wavelengths over 2.3 μm. Applying laboratory equipment to measure the harmonic gas spectra, we have successfully detected CO and CH_4 simultaneously in ppm range with subtraction of a complex background pattern attributed to the laser PI characteristic. During sensor operation, the background can not be simply subtracted but reduced by a factor of 5 using a high pass filter, so that the filtered background peak to peak level corresponds to an absorption of $2 \cdot 10^{-4}$. Extrapolating the performance of existing systems, at least 42 ppm CO resolution (maximum error) can be achieved with 2×20 cm absorption path length, 0.1 s time resolution and high pass filtering. The system resolution is then limited by the background pattern compared to the InP 2.3 μm laser [20]. However, these are worst case considerations because the performance of the sensor can be improved by a curve fit. If the background pattern could be totally eliminated, a detection resolution of 1 ppm m CO (standard deviation) would be expected with 1 Hz bandwidth.

We have found that the complex background pattern in the second harmonic spectrum is caused by kinks in the PI characteristics. These are not associated with mode flips because the device remained in stable single mode operation during spectrum scan with current/temperature. Moreover, there is no rotation in the far field emission pattern during current tuning. The reason for the kinks in the PI characteristics is still unclear and expected to be solved in the ongoing development.

Acknowledgments

The authors gratefully acknowledge the financial support by the Federal Ministry of Education and Research of Germany (Project 'NOSE', contract No. 13N8772) and by the European Union (Project 'NEMIS', contract No. 031845)

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