Compact VCSEL-based CO_2 and H_2O sensor with inherent wavelength calibration for safety and air-quality applications

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Abstract: A compact CO_2 and H_2O laser spectroscopy sensor based on cost-efficient vertical-cavity surface-emitting lasers for safety and air-quality applications is presented. It implements inherent wavelength calibration to achieve self-monitored and calibration-free operation during sensor lifetime.

OCIS Codes: 140.7260 (Vertical cavity surface emitting lasers); 300.6360 (Spectroscopy, laser)

1. Introduction

Carbon-Dioxide (CO_2) is an important gas for environmental, industrial and medical applications. The background level of CO_2 present in outside air (~400 ppm) is very small compared to the amounts of CO_2 that are exhaled by humans or animals (up to 40000 ppm). In closed rooms the CO_2 concentration then rises strongly when one or more persons are present, which happens more often during wintertime. CO_2 sensors allow for an optimized air conditioning, and the energy savings can lead to an important cost reduction for hotels and large office buildings. CO_2 monitoring for automotive applications serves the same purpose [1]; with the possible further application of detection of dangerous CO_2 levels, which may occur when the future refrigerant for air-conditioning systems R744 (CO_2) leaks to the cabin of the automobile. Although CO_2 itself is not poisonous, high ambient CO_2 concentrations (vol% range) inhibit the CO_2-O_2 gas exchange in the lung, and can cause a life threatening situation, even if still enough O_2.is present. Besides leaking of large amounts of CO_2 in industrial or environments with volcano activity, high CO_2 levels may occur in any closed compartments where biological fermentation takes place that steadily generates CO_2 which may accumulate on the ground (e.g. in silos, cellars for winemaking and caves). Therefore, CO_2 sensors for these applications are strongly required and have to fulfill several safety requirements like long-term stability, reliability and fail-safe operation. These requirements are difficult to meet with the most prominent/conventional industrial solution for CO_2 detection: NDIR spectrometry (Non-dispersive infrared spectrometry). It uses a broadband lightsource (glow lamp, LED) a filter and a detector to detect the light attenuation due to the fundamental CO_2 absorption band at 4.3 µm wavelength [1, 2]. Also electro-chemical sensors [3] and experimental chemical sensing techniques for CO_2 exist. However, all electrochemical or NDIR-spectrometry based sensors do not have the ability of self-monitoring and have to be replaced or tested from time to time if reliable operation is needed. In contrast, laser spectroscopy based sensors do not suffer from these drawbacks. Drift of the laser emission wavelength, attenuation or complete blockage in the optical path by contamination as well as other aging effects can either be fully compensated or at least inherently self-monitored. Furthermore, due to the narrowband detection the cross-sensitivity to other gases of laser spectroscopy sensors is usually lowest among all sensing principles and sensitivity highest among spectroscopic sensors with same optical pathlength. Widespread use of these sensors is limited by the price of the necessary laser diode. Promising, more cost efficient solutions are based on vertical-cavity surface-emitting lasers (VCSELs) that have several advantages over DFB edge-emitters in mass production like on-wafer testability. Existing laser based sensors for CO_2 are either complex instruments for isotopic ratio measurements operating in the MIR at 4.3 µm [4], based on fibers and multipass cells at 1.5 µm [5] or at 2.0 µm with several cm optical path length but using DFB lasers and conventional line-locking [6].

2. Sensor Design

Besides their low-cost potential, VCSELs have other significant advantages compared to DFB lasers, like low power consumption and wide current tunability. The in this sensor utilized 2 µm VCSEL is able to scan at least several nm via current tuning covering several CO_2 and H_2O lines (Fig. 3). Because CO_2 and H_2O have at least concentrations of 400 ppm and 10000 ppm in ambient air, absorption lines always exist in the scanned spectrum of ambient air. The absorption features are detected and assigned to theoretical line data with a heuristic algorithm that also works under all concentration ratios of H_2O and CO_2, provided the CO_2 stays above its ambient level of 400 ppm. By comparing with theoretical line positions the wavelength scale for the scanned spectrum is obtained. Compared to ordinary line locking, where only the wavelength offset is adjusted, also the linear and quadratic tuning coefficient are determined without having a reference etalon, as it was demonstrated for CO sensing at 2.3 µm in [7]. It is thus possible to employ an efficient linear spectral curve fitting routine which allowes for a measurement rate of 10 Hz with a 20 MHz, 16 bit microcontroller. In Fig. 1 the optical cell design with a folded optical path (20 cm) is shown. Every few seconds a wide spectral scan is done to recalibrate the wavelength scale (Fig. 3). A linear curve-fit with computed reference spectra is done in 200 ms intervals for the narrow wavelength scans (Fig. 4) that are used to determine the CO_2 and H_2O concentration.

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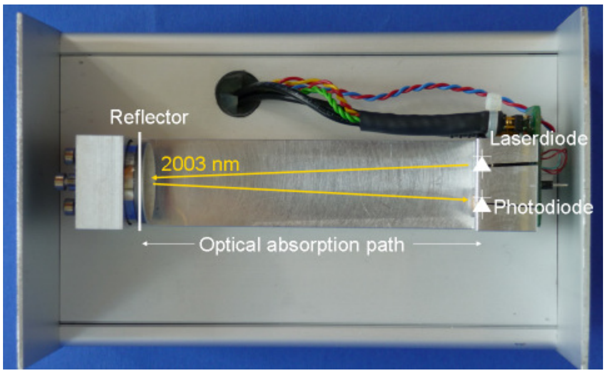

Fig. 1: Schematic of the sensor optics. The optical pathlength is 2 x 10 cm. The 2.0 µm VCSEL and the InGaAs photodiode are mounted side by side.

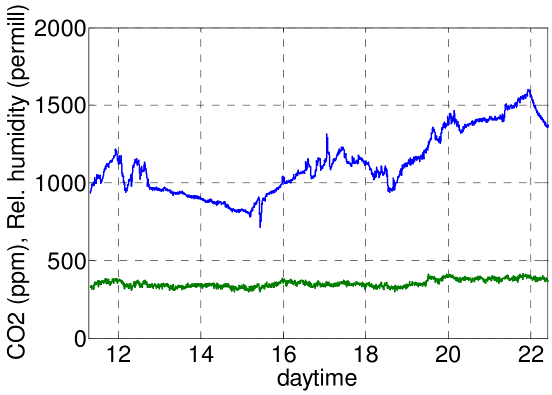

Fig. 2: Measured CO_2 concentrations (blue) and relative humidity (green) during a day inside a household. The averaging time was set to 30 seconds.

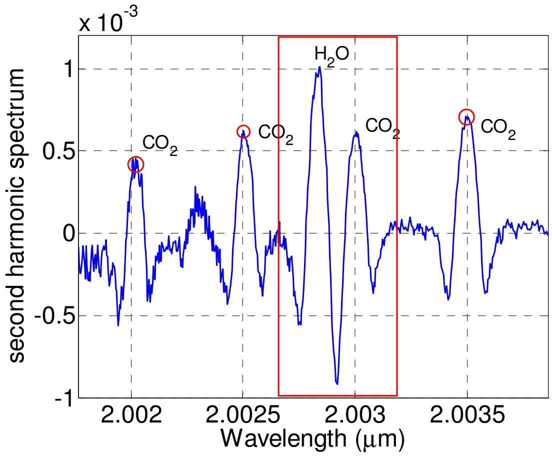

Fig. 3: The wide spectral scan for wavelength identification. At least 3 CO_2 absorption lines (red circles) serve as wavelength markers to determine the linear and quadratic coefficients of the wavelength scale. The red box specifies the wavelength range of the narrow scan.

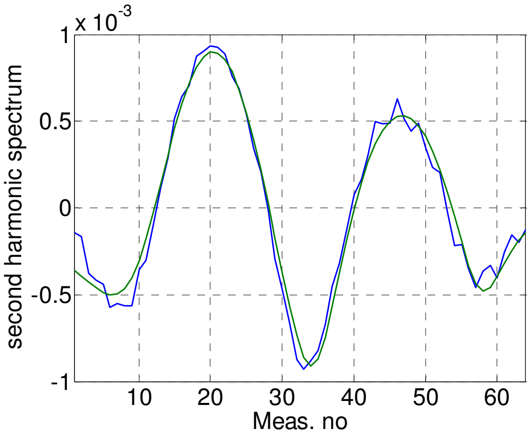

Fig. 4: The narrow spectral scan (blue) and corresponding linear curve fit (green) with computed spectra from theoretical absorption line data. It consists of overlapping H_2O (right, 2.0028 µm) and CO_2 (left, 2.003 µm) absorption lines.

The sensor was tested during a day inside a household; with averaging time set to 30 seconds (Fig. 2). Although relative humidity stays almost constant during a day, the CO_2 concentration varies strongly. Between 13h and 15h and after 22 h no persons were in the room so a decay of CO_2 is observed. With presence of one or more persons a steady concentration increase is observed (despite the very high volume of the room of > 300 m^3), whereas positive or negative peaks correspond most likely to open windows or persons standing near to the sensor.

3. Conclusion

A compact TDLS-based CO_2 and H_2O sensor is presented. It is based on a single 2.0 µm VCSEL and employs a single reflective 20 cm long optical cell. The sensor employs a repetitive inherent wavelength calibration every few seconds using broad wavelength scans covering at least four CO_2 absorption lines that serve as wavelength markers. This is possible due to the large current tuning range provided by VCSELs. Besides compensation of wavelength drift due to laser aging, knowledge of the full wavelength scale – not only wavelength offset – enables the use of an efficient linear curve fitting routine that is particularly suited for microcontrollers with low computation power available. Compared to other CO_2 sensors a laser based sensor allows for self-monitored operation that can be used to build fails-safe and calibration-free sensors, where long-term stability and reliability is needed to be guaranteed e.g. in safety applications.

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