

# A Calibration-free Mid-Infrared TDLAS Sensor for Stand-Off Detection of Carbon Dioxide operating at 2004 nm

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## Summary:

This work presents a system concept for remote emission sensing, focusing of the design and validation of a calibration-free wavelength modulation spectroscopy (CF-WMS) approach. We show the applicability of a CF-WMS system for the detection of CO<sub>2</sub> emissions of on-road vehicles with laboratory validation measurements as well as first field tests.

**Keywords:** Remote Emission Sensing, Calibration-Free Wavelength Modulation Spectroscopy, TDLAS, Carbon Dioxide Monitoring, Vehicle Emissions

## Introduction:

Emission regulations employed by institutions such as the European Union aim to reduce the emissions by vehicles on the road. These measurements have shown success for compliant vehicles, yet still 90 % of on-road emission are caused by 15 % of vehicles, commonly known as high emitters [1]. Identifying those high-emitting vehicles can help in the overall reduction of on-road emissions.

Remote Emissions Sensing (RES) has been shown to be a suitable tool for emission monitoring. In RES, the emissions of vehicles are measured by measurement systems installed at the roadside. This allows for a non-invasive measurement on the one hand, while on the other hand captures thousands of vehicles per day under normal driving conditions.

In the field of RES CO<sub>2</sub> emissions are commonly used in the determination of fuel related emission factors. Therefore, an accurate and reliable measurement of the emitted CO<sub>2</sub> and pollutant concentration is necessary.

In this work we present a system for calibration-free wavelength modulation spectroscopy for RES, characterization details and measurement results. The characterization of laser parameters omits the need for reference measurements during operation, while the principle itself has been shown to provide high accuracy, even in harsh conditions [2].

## System Concept:

For our measurement system we use a DFB laser diode for the selected CO<sub>2</sub> absorption line at 2004 nm, as it shows limited cross interference

to H<sub>2</sub>O while having suitably high absorption, even at ambient CO<sub>2</sub> concentrations. Our system is additionally equipped with an ICL targeting NO<sub>2</sub> at 3421 nm, and an ICL for NO at 5263 nm is prepared. Furthermore, we aim to involve NH<sub>3</sub> measurements in the future.

## Measurement Methods:

Wavelength Modulation Spectroscopy (WMS) is a specialized application of Tunable Diode Laser Absorption Spectroscopy. Here the injection current of the DFB laser is modulated by two superimposed sinusoidal signals: a low frequency scan ( $f_s = 11.92$  Hz) and a high frequency modulation ( $f_m = 70$  kHz).

The resulting amplitude modulation of the absorption feature is demodulated at  $f_m$  and  $2f_m$  using a Lock-In amplifier. From the demodulated signals the resulting amplitude is calculated. As background absorption as well as nonlinear intensity effects can occur, both background and absorption  $2f$  signals must be normalized by the laser intensity contained in the  $1f$  signal [3]:

$$S_{2f/1f} = \sqrt{\left(\left(\frac{X_{2f}}{R_{1f}}\right)_{\text{raw}} - \left(\frac{X_{2f}}{R_{1f}}\right)_{\text{bg}}\right)^2 + \left(\left(\frac{Y_{2f}}{R_{1f}}\right)_{\text{raw}} - \left(\frac{Y_{2f}}{R_{1f}}\right)_{\text{bg}}\right)^2} \quad (1)$$

Here  $X_{2f}$  and  $Y_{2f}$  are the in-phase and quadrature components of the Lock-In Amplifier at  $2f$ , while  $R_{1f}$  is the root-sum-square of the  $1f$  outputs [3].

## Measurement of Laser Parameters:

The emitted light of the laser can be described by its intensity and wavelength response. Accurately determining those laser parameters allows for a detailed modeling of the absorption process [4]. By simulating the Lock-In detection as well,

the signal, as detected in the measurement, can be modeled. This model is then used to determine the concentration from the measured signal by a fitting process.

### Validation of Signal Reconstruction:

The CF-WMS approach was validated in terms of the reconstruction of concentration values from the measured WMS signal. Using a gas diluter, a range of gas concentrations were introduced into a gas cell with a pathlength of 2 m. Absorption spectra were recorded for each concentration. To account for absorption by ambient CO<sub>2</sub> concentrations the gas cell was filled with pure N<sub>2</sub> to record a background signal. Signals were averaged over 16.7 s.

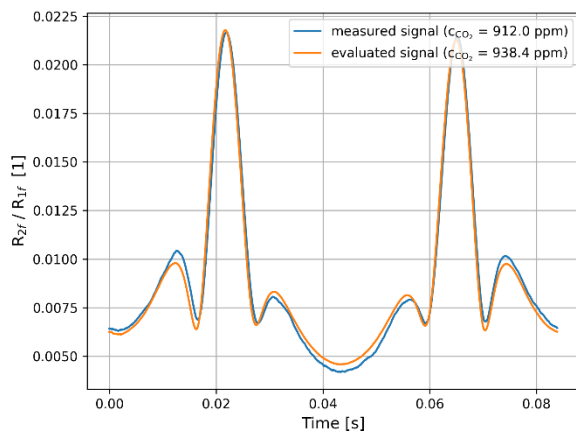


Fig. 1: Comparison between a measurement of 912 ppm CO<sub>2</sub> over a pathlength of 2 m and the corresponding evaluated concentration.

In Fig. 1 an example of measurement and evaluated spectrum is given. The evaluated measurement of the CO<sub>2</sub> concentration shows only an error of 2.98 %, which considering the low concentration and short pathlength shows to usability of this system concept for RES applications.

### On-Road Measurement:

The CF-WMS system was further tested in a real-world scenario on the road. With the spectroscopy unit placed on one and the reflector unit

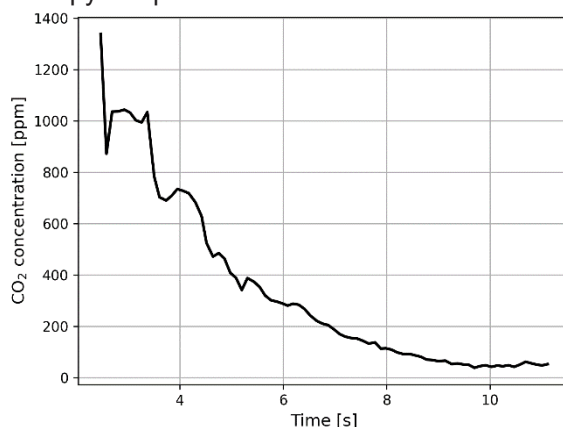


Fig. 2: Measured pathlength-averaged CO<sub>2</sub> concentration of a passing diesel vehicle.

on the side of the road a measurement pathlength of 10.18 m was realized. A diesel passenger car was used as a test vehicle. The considered measurement event started 2.5 s before the vehicle entered the measurement location. The Lock-In outputs were recorded for a total time of 22 s.

Data collected before the vehicle entered the measurement location was used as the background signal and used in the background correction (1). The modeled absorption was then fitted to the background corrected signal to obtain the average CO<sub>2</sub> concentration over the pathlength of 10.18 m. In Fig. 2 the evaluated CO<sub>2</sub> concentration during the measurement event is shown.

### Conclusions and Outlook

The presented CF-WMS setup has been validated in laboratory measurements showing its potential for a calibration free measurement of CO<sub>2</sub> concentrations, while first measurements in RES applications showed promising results.

The work regarding additional laser source for the detection of the pollutants described above is ongoing. Superimposing the laser beams for all analytes allows us to measure all concentrations simultaneously.

By combining this measurement approach with a gas imaging technique further enhances the systems capabilities to measure absolute concentrations for all targeted analytes [5].

### References

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