Originally published as:

Eberhardt, A., Scholz, L., Westermann, S., Sachs, T., Langer, M., Wöllenstein, J., Palzer, S. (2014): Low cost, mobile sensor system for measurement of carbon dioxide in permafrost areas. - *Procedia Engineering*, *87*, pp. 1318—1321.

DOI: http://doi.org/10.1016/j.proeng.2014.11.690

Available online at www.sciencedirect.com

ScienceDirect

Procedia Engineering 87 (2014) 1318 – 1321

Procedia Engineering

www.elsevier.com/locate/procedia

EUROSENSORS 2014, the XXVIII edition of the conference series

Low cost, mobile sensor system for measurement of carbon dioxide in permafrost areas

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Abstract

In this work a novel concept based on low power semiconducting, mid infrared components and new, low cost measurement cells for use in harsh environmental conditions, such as permafrost areas, is presented. Due to the small changes of the environmental carbon dioxide (CO_2) concentration in this area a high resolution of 5 ppm CO_2 is required. The current sensor design achieves a resolution of up to 6 ppm CO_2 and offers further optimization potential at overall low costs.

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Peer-review under responsibility of the scientific committee of Eurosensors 2014

Keywords: permafrost; low cost; mid infrared; carbon dioxide; optical; III-V semiconductor; MIR-LED; photoconductor, photometer

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1. Introduction

Accurate predictions on emissions of greenhouse gases (GHG) are one of the most important components in the development of next generation Earth System Models (ESM). This requires the measurement of GHG fluxes, especially carbon dioxide (CO_2), in a wide range of spatial and temporal scales [1]. One of the regions with a high

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Peer-review under responsibility of the scientific committee of Eurosensors 2014
doi:10.1016/j.proeng.2014.11.690

potential of GHG-emissions are the permafrost regions of the northern hemisphere. In a warmer future climate, these regions are susceptible to increased thawing and could potentially emit large amounts of CO_2 [2, 3]. Consequently, the monitoring of both CO_2 concentrations and fluxes are important for the development of more reliable ESMs. However, low-cost, energy efficient yet reliable and precise measurement tools for CO_2 to cover large permafrost areas are scarce.

The requirements for sensors to be used in this application include high resolution of approximately 5 ppm at background concentrations in the order 400 ppm CO_2, a high reliability in terms of stability towards humidity, pressure and temperature changes as well as low energy consumption. Currently researchers use complex and expensive systems that are unsuitable for large scale deployments [4–6]. The most common way to determine carbon dioxide fluxes into and out of the soil is the so called eddy covariance method. Unfortunately, due to the complex sensor hardware, technology upscaling of this method is impeded. In order to provide climate researchers with a hardware tool that can form the central building block of a sensor network with hundreds to thousands of nodes, reliable low-cost approaches are needed.

Recently, several groups started researching concepts that might combine high precision and low-cost, simple technologies. S. So et al. developed two systems, one based on QEPAs and one state of the art TDLS system, which demonstrate low energy consumption and could achieve a resolution which is needed for this application [7, 8]. However, both concepts rely on a laser source in the mid infrared spectral range which is too expensive for implementation in large scale networks. Other groups concentrate on simple single channel photometer setups based on III-V small band gap semiconductors [9–11]. They achieved accuracies in the range from 200 ppm to 20 ppm, but with the disadvantage of comparatively long averaging times and optical paths length too short for an accuracy of 5 ppm.

2. Results

To meet all the necessary criteria the system should be based on a simple and robust setup. Consequently, we choose a photometer setup based on semiconducting components for both radiation source and detector. Hence, the setup does not require moving parts which is essential for robust low cost applications in harsh environments. The radiation source is a mid infrared LED with a centre wavelength at 4.3 µm and a spectral width of 0.8 µm from LED Microsensor NT, LLC. In order to pick the right detector several test measurements with photodiodes and photoconductors with peak detectivities around 4.3 µm were performed. Because of the performance of the photodiodes in this range we selected photoconductors which have a good photosensitivity but also show strong temperature dependence. This requires powerful thermal compensation techniques to account for changes in the ambient temperature. For this task the ambient temperature is recorded during measurements. Because of the exponential temperature dependence of the dark resistance, an exponential function was used to derive the correction function of Figure 2 from the temperature:

$$f_{cor} = \exp\left(A \cdot \left(1 - \frac{T}{T_0} \right) \right) \tag{1}$$

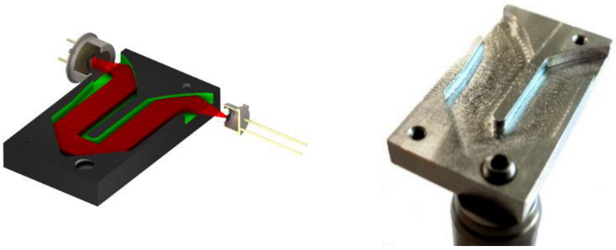

Fig 1. (left) Schematic view of the optical waveguide of the sensor with a designed optical path length of 7.6 cm. (right) Picture of the final measurement cell fabricated in aluminum using a CNC milling machine. The quality of the surfaces can be further enhanced using other fabrication methods.

The correction function depends on the current temperature T, the reference temperature and the constant A. This constant is system dependent and must be evaluated in calibration measurements. Here this constant has a value of 14.5. To keep the dimensions of the sensor small, the optical path was folded with a measurement cell made from aluminium with an effective optical path length of 7.6 cm and overall dimension of (2 x 3 x 1) cm^3 (Figure 1).

In order to check the sensitivity and stability of the system, a long term measurement with different concentration levels was performed. For this task the sensor was placed in a measurement chamber in the laboratory and a gas delivery system was used to mix concentrations between 0 ppm and 5,000 ppm in 500 ppm steps in nitrogen (N_2). Additionally a 10,000 ppm step was added in order to confirm sensitivity simulations. The temperature of the system was measured with a platinum reference resistor (PT1000). The results of this measurement are presented in Figure 2. The first diagram shows the normalized sensor data as well as the correction function which is calculated from the temperature measurement in the second diagram using equation (1). Because of the correction the strong signal variations caused by temperature changes especially in the beginning could almost be removed completely. From minute 1,130 onwards the concentration was kept constant to evaluate the long term stability of the baseline. A standard deviation of 0.0014 was achieved over a period of several days. For each concentration step the mean value and standard deviation was calculated. Figure 3 (left) shows the result together with simulations, performed to confirm the optical path of the measurement cell. On the right side of Figure 3 the spectra of all used optical components are shown. Because of the wide spectral range of the LED an interference filter was added to the optical path. This should increase the sensitivity of the system depending on the position and spectral width of the filter. In the lower concentration range up to 5,000 ppm the simulation fits very well to the measured data. The deviation at 10,000 ppm is caused by the change of volume flow from 2.0 l/min to 1.0 l/min due to the restricted range of our mass flow controllers. Based on these results a long term noise equivalent concentration (NEC) of 12 ppm and in short terms conditions a NEC of 6 ppm was achieved. Additional measurements turned out that the filter does not increase the sensitivity of the complete sensor as much as theoretically expected. The sensor response increased like simulated, but the signal to noise ratio was decreased, due to the smaller signal and increased noise. Hence, more attention should be payed to the intensity of the LED and the transmission and length of the optical path to achieve an accuracy in the range of less than 5 ppm.

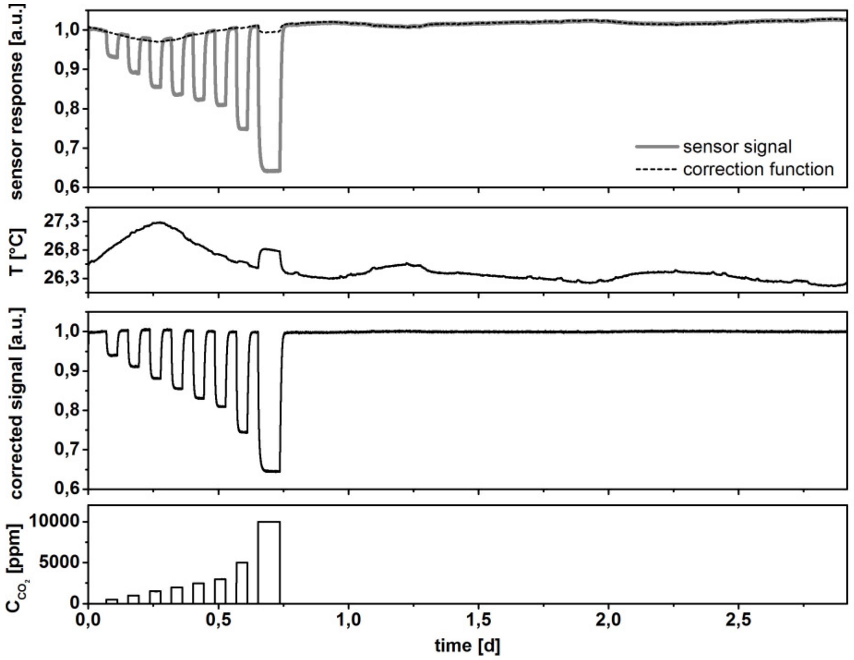

Fig 2. Results of a long term measurement over almost 3 days with changing CO_2 concentrations in dry nitrogen (N_2). The first part shows the normalized sensor response and the correction. The corrected signal is shown in the third diagram. It features a good long term stability.

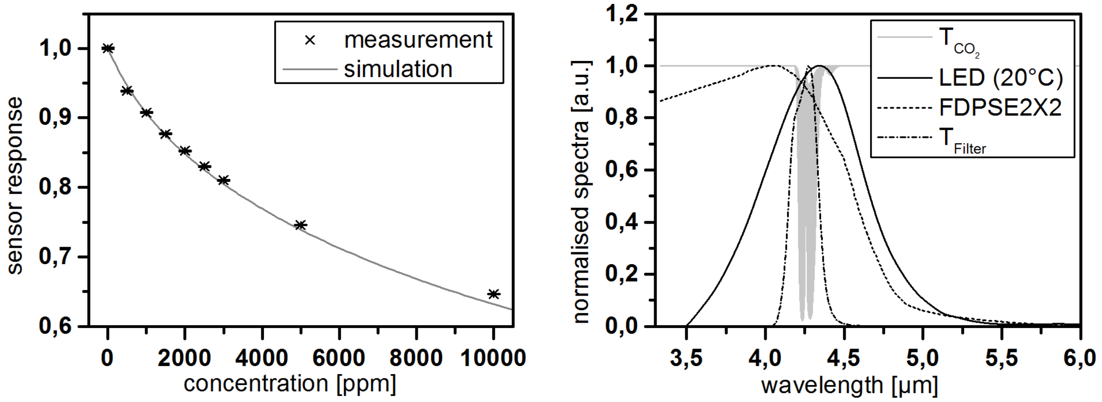

Fig 3. (left) Comparison of CO_2 concentration measurements carried out in the laboratory and simulated sensor response. (right) spectra of all optical components implemented in the sensor.

3. Conclusion

Here we presented the current status of our ongoing work to develop a novel CO_2 sensor setup which is designed for harsh environmental conditions and high accuracy. In order to make the setup robust the design is as simple as possible. After temperature correction of the sensor signal the stability of the sensor reading is improved significantly. With an optical path of 7.6 cm a noise equivalent power (NEP) of 12 ppm in long term conditions was achieved.

Acknowledgements

This work was supported by a grant from the German Federal ministry for Economic Affairs and Energy under grant number KF2162023DF3 (iSens CO2).

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