URN (Paper): urn:nbn:de:gbv:ilm1-2014iwk-054:7

CHARACTERIZATION OF NON-DISPERSIVE INFRARED GAS DETECTION SYSTEM FOR MULTI GAS APPLICATIONS

M. Silinskas[1)], R. Mikuta[1)], R. Bourouis[2)], S. Kloos[2)], E.P. Burte[1)]

[1)] Otto von Guericke University Magdeburg, Institute of Micro and Sensor Systems (IMOS)
[2)] J. Dittrich Elektronic GmbH, Baden-Baden

ABSTRACT

In this work, we present a low cost multi gas detection system for a simultaneous measurement of up to four kinds of gases. The main conclusions are based on the investigation of CO_2 gas concentration, which are also supported by CH_4 gas and H_2O vapor. It was found that the continuous heating of the IR source and the absolute values of thermopile voltages are not suitable parameters for the gas detection because of high sensitivity to the influence of temperature and/or gas flow parameters. The sine like signal is preferential for our measurement system. The amplitude of the sine is very stable and is proportional only to the concentration of particular gas (according to the optical filter) and is not dependent on the concentration of other gases or on temperature. In this way, the CO_2 gas concentration can be measured from 50 ppm to 400 000 ppm with the same measurement setup. However, the lower detectable concentration of CH_4 was about 500 ppm.

Index Terms: Thermopile, Non dispersive IR, gas concentration, CO_2, CH_4.

1. INTRODUCTION

Gas composition monitoring experiences an increasing importance together with the opening up of new areas of application. Presently single gas detection systems are used in many fields. Despite this fact the detection of further gases, for example humidity and hazardous gases and not only CO_2 in indoor gas monitoring [1] or CO_2 and hydrogen sulphide additionally to CH_4 in biogas are interesting [2].
Non dispersive infrared (NDIR) gas measurement systems are widely used because of their high selectivity, sensitivity, simplicity, and long-term stability [3]. These systems are based on the detection of light intensity variation caused by IR absorption of specific molecules. One kind of the possible detectors used for this purpose is a thermopile sensor. Such sensors are highly efficient, low cost with low power consumption [4].
In this work, we present a low cost multi gas detection system able to simultaneous measure the concentration of the following gases: CO_2, CH_4 and H_2O.

2. EXPERIMENTAL

The multi gas detection system is shown in Fig.1. This system consists of an IR lamp, an absorption chamber, a filter array, and an IR sensor array.

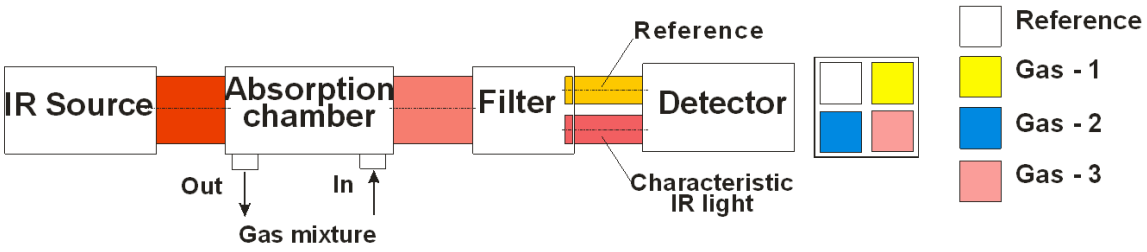

Fig.1. Multi gas detection system.

A miniature lamp HSL 5/115/s was used as an IR radiation source. The voltage across the bulb was modulated using different signal profiles supplied by a microcontroller. The gases were introduced into the absorption chamber with an integrated reflector. Different absorption lengths ranging from 3 cm to 8 cm were investigated. Three optical narrowband filters were used for the selection of the characteristic wavelength region corresponding to the specific species of molecules and one filter (3.95 µm) was used as the reference without any cross-sensitivity to the investigated or atmospheric gases. Synthetic air, CO_2, CH_4, and H_2O (bubbler system) gases were dosed by mass flow controllers, and the different gas concentrations were achieved by varying the ratios of the gas flows.
IR sensor arrays (2x2) were produced by X-FAB® using silicon technology for MEMS. Every single sensor (4.5 mm x 4.5 mm with sensitivity of more than 150 Vmm^2/W) contains about 700 thermocouples. The thermovoltage generated over these thermocouples was electrically amplified by a factor of about 35.
The algorithm that has been developed to process the signal of the thermopile is based on a harmonic regression which is a linear regression in which the predictor variables are trigonometric functions of a single variable. Indeed the IR-source is modulated with a sinusoidal signal in order to obtain a thermopile signal having a sinusoidal profile as described below:

$$U(i) = U_0 + U_1 \cdot \sin\left(\frac{(2i+1)\,\pi}{n} + \varphi_0\right) = s_0 + z_1(i) \cdot s_1 + z_2(i) \cdot s_2$$

where s_j and $z_j(i)$ are, respectively, the regression coefficients and the independent variables. These parameters are defined through the following equations:

$$s_0 = U_0;\ s_1 = U_1 \cos(\varphi_0);\ s_2 = U_1 \sin(\varphi_0)$$

$$z_0(i) = 1;\ z_1(i) = \sin\big((2i+1)\,\pi/n\big);\ z_2(i) = \cos\big((2i+1)\,\pi/n\big)$$

This multiple linear regression could be simply represented in the matrix form as follows:

$$\underline{u}(i) = \underline{z}(i,j) \cdot \underline{s}(j)$$

The signal is sampled every 2ms over a period of about 1 second. We take 256 measurements $\underline{u}(i)$ per cycle for one estimate. The resulting regression coefficients are then determined using the following equations:

$$\underline{s}(j) = \begin{cases} s_0 = \frac{1}{256} \times \sum_{0}^{255} u(i) \\ s_1 = \frac{2}{256} \times \sum_{0}^{255} u(i) \times \sin\left(\frac{(2i+1)\,\pi}{n}\right) \\ s_2 = \frac{2}{256} \times \sum_{0}^{255} u(i) \times \cos\left(\frac{(2i+1)\,\pi}{n}\right) \end{cases}$$

The offset of the thermopile signal is equal to s_0, however the amplitude U_1 and the phase φ_0 of the signal depend on the coefficients s_1 and s_2 as follows:

$$U_1 = \sqrt{({s_1}^2 + {s_2}^2)}, \qquad \varphi_0 = arctan\left(\frac{s_1}{s_2}\right)$$

The evaluating software implemented onto the microcontroller of the sensor compute the amplitude that is directly related to the target gas concentration, as well as the phase of the sensor signal. If only one estimate of a signal over a one period is computed with the method described so far, the output signal typically will be rather noisy. The remedy is to take the average of a certain number of estimates. The averaging will reduce the standard deviation by a factor of $\sqrt{Number\ of\ estimates}$. A moving averaging over 21 estimates have been implemented into the processing algorithm to reduce the standard deviation by a factor of about 4.5.

3. RESULTS AND DISCUSSION

Typical output signals generated on continuously and sine modulated IR illuminated Thermopiles are shown in Fig. 2. The thermopile voltage from continuous IR radiation is very noisy and has significant shift depending on the measurement time, which can be caused by temperature differences of the flowing gases or by heating effects in the measurement system. Therefore, the alternating voltage was used. Many light modulation profiles like $\sin^{1/4}$ – and square-wave, have been investigated but the best stability of the output signals was observed by a sine modulation. The typical thermal voltages using sine modulated IR light are shown in the Fig. 3. In this measurement synthetic air and mixture of synthetic air and carbon dioxide have been applied to measure the variation of IR radiation due to gas absorption. The noise and shifting of the thermal voltage are a little bit reduced compared to the continuous signal but remain sufficiently high. The absolute value of the thermal voltages decreases with increasing CO_2 gas concentration for the "CO_2" channel (CO_2 optical filter). As well, the similar (little lower) decrease is also observed for the "reference" channel (reference optical filter). As a result the difference between the "reference" - and "CO_2" signals is not sufficient to measure gas concentration. Therefore, the absolute value of the thermopile voltage is not suitable to measure the gas concentration. However, Fig. 3 shows that the sine amplitude is also related to the gas concentration and, contrary to the absolute voltage, the changes due to gas absorption are observed only for the "CO_2" channel. Thermopiles illuminated with sine modulated IR light show better and more stable output signals that are related only to the concentration of the specific gas (depending on the used optical filter) and does not depend on the other gases or various flow parameters. This fact is also true for other gases and optical filters. Therefore, the use of a sine modulation (particularly sine amplitude) significantly enhances stability and sensitivity of the measurement system.

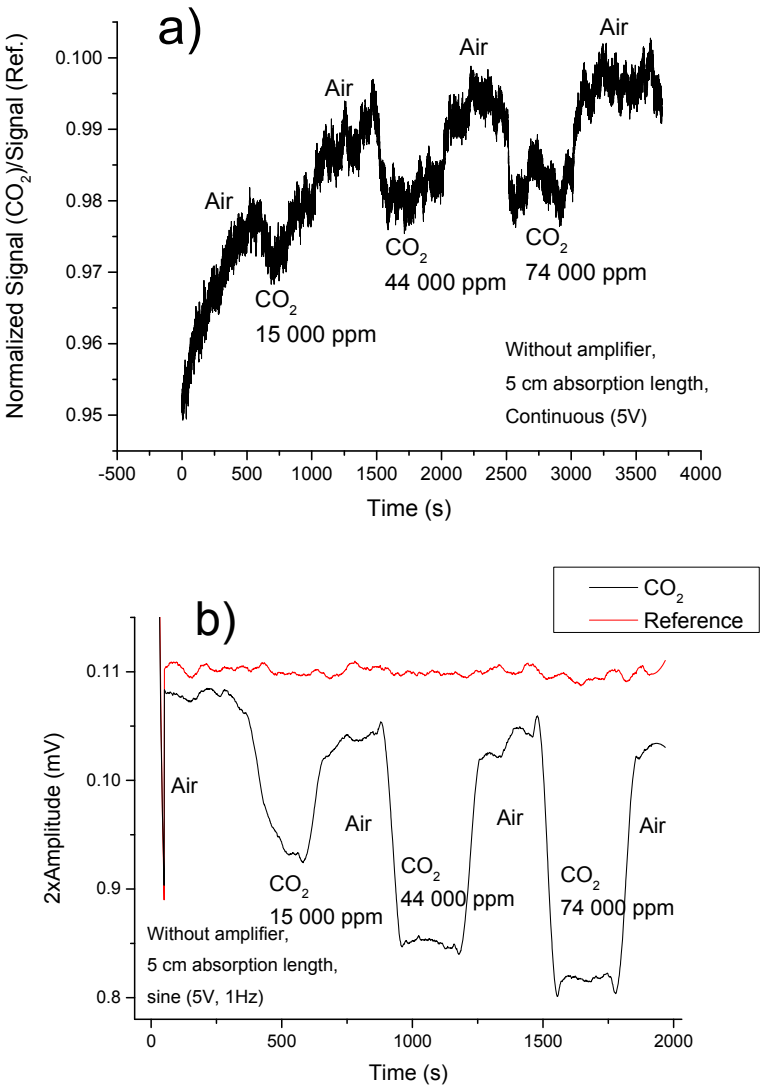

Fig. 2. The ratio of "CO_2" to "Reference" signals using continuous (5 V) IR source (a) and amplitude of thermal voltage (b) using sine IR source.

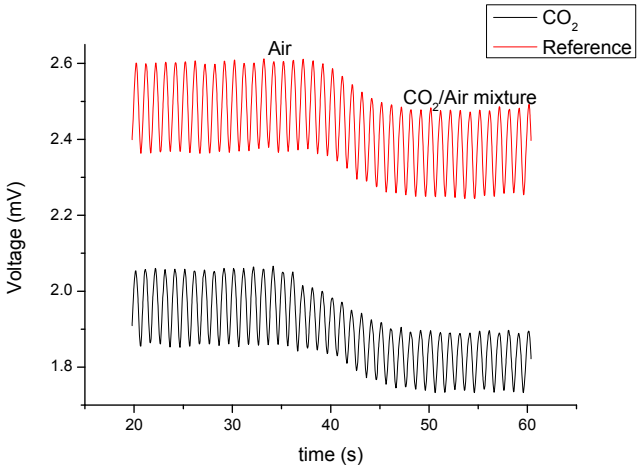

Fig. 3. Thermal voltages of the gas sensor using CO_2 and reference optical filters.

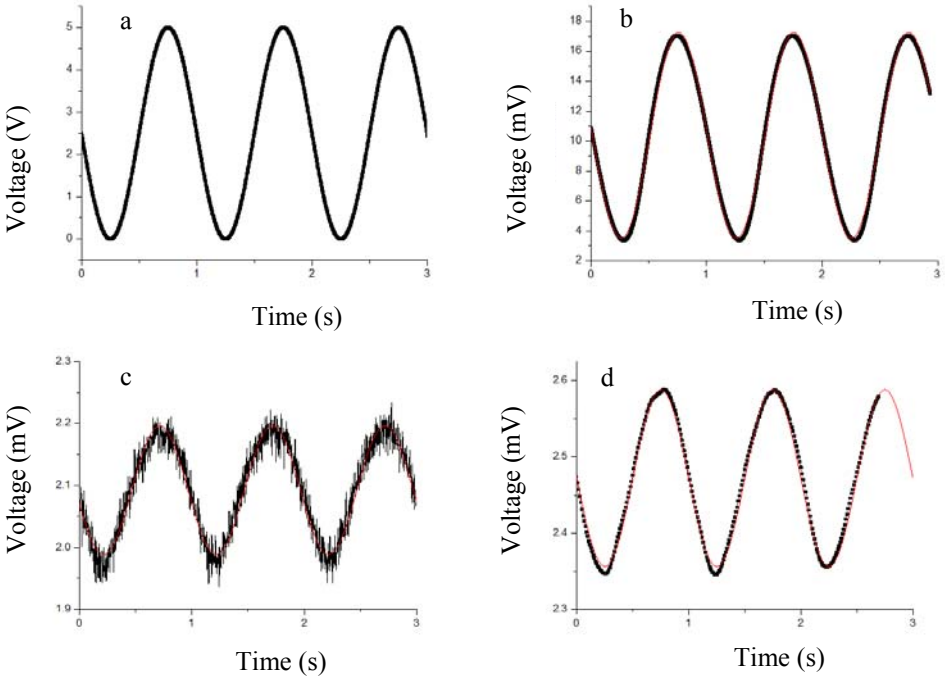

Fig. 4. The Signals: a – of lamp, b – without optical filter and with low pass filter, c – with optical filter and without low pass filter, and d – with low pass filter. The red line is a fitting of ideal sine.

Fig. 4 shows the shapes of the different signals using sine heating of the IR source. The ideal sine (see Fig. 4a) of the electrical voltage (256 values per one period) put on to the lamp is:

$$V(t) = V_0\{\sin(2\pi \cdot t + \varphi_0) + 1\}$$

where V_0 = 2.5 V and φ_0 = 0.
A little deformed sine of thermal voltage is detected from the sensor (see Fig. 4b - 4d). The shape of the thermal voltage without an optical filter is very close to the input signal (Fig. 4b). Additionally, a low pass filter reduces the noise but does not change the form of the sine signal (Fig. 4c-4d). These facts suggest that some parasitic effects, such as IR heating of the optical filter, occur but the influence of such effects is very small and can be neglected for further calculations.

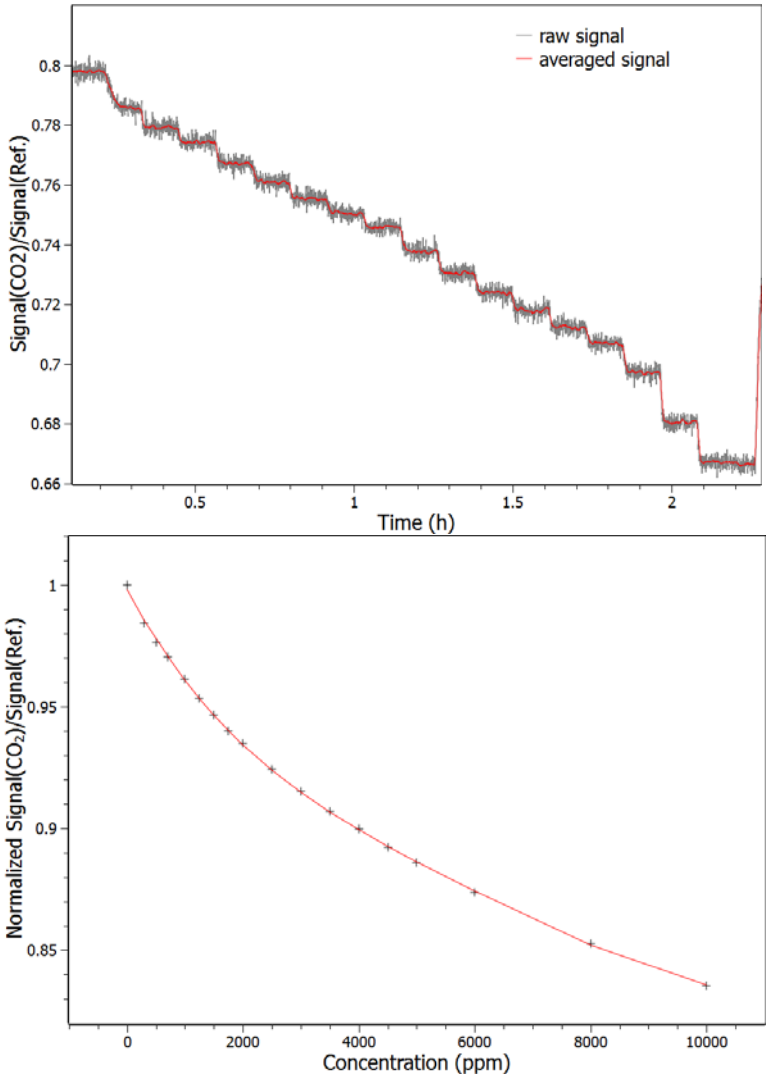

Fig. 5. Ratio between amplitudes of the "CO_2" and "Reference" channels as a function of CO_2 concentration.

Fig. 5 indicates the variation of "CO_2" channel amplitude depending on different CO_2 gas concentrations. In the range between 0 ppm and 10 000 ppm the amplitude decreases exponentially with increasing CO_2 concentration. At the same time no changes were observed in other channels. The standard deviation and the noise are about 50 ppm and 250 ppm, respectively. The use of moving average (21 values) method allows reducing the standard deviation about 5 times and the noise about 8 times. The same character of amplitude variation is true till about 40 000 ppm. With higher concentrations the saturation of the amplitude became significant (Fig. 6) and after about 400 000 ppm it was impossible to detect any signal differences.

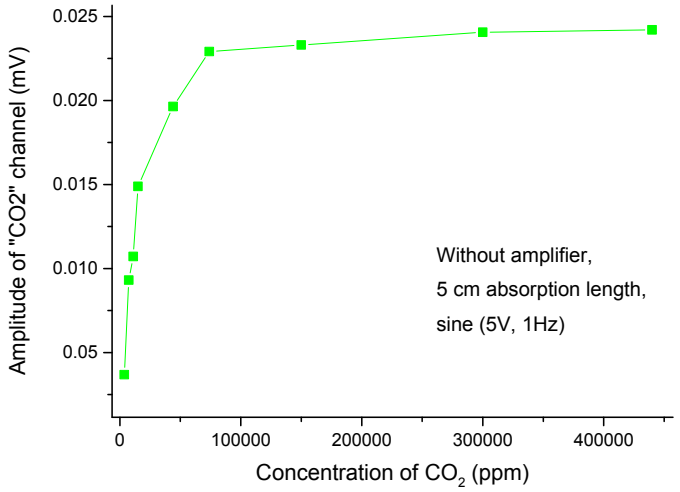

Fig. 6. CO_2 absorption as a function of the CO_2 concentration in gas mixture.

The sensitivity and measurement error are not the same in the whole measurement range. The sensitivity of the measurement is shown in the Fig. 7. The maximal sensitivity was observed for very low CO2 concentrations and it should be about 1 % per 100 ppm of CO_2. However, the measurement error is very high at very low concentrations. Further, the sensitivity nonlinearly decreases as the concentration of the investigated gas increases.

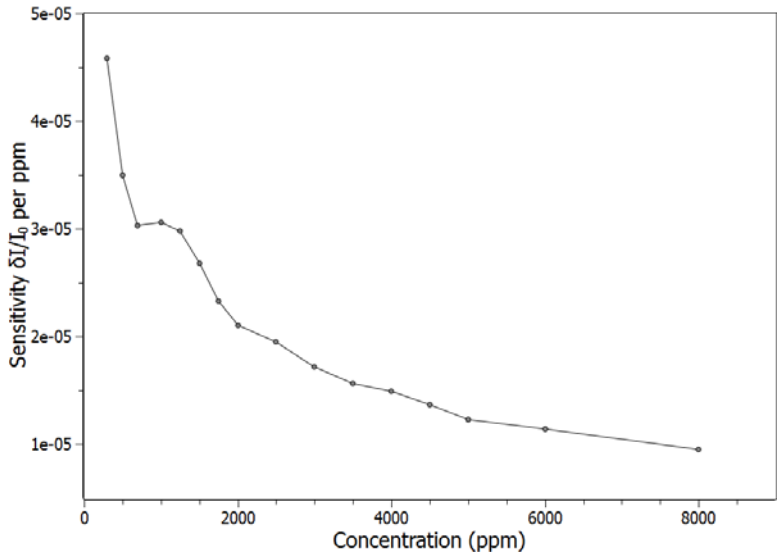

Fig.7. Sensitivity of the "CO_2" channel.

This means that the CO_2 concentration can be measured with higher precision between 100 ppm and 80 000 ppm and with a low one between 50 ppm and 400 000 ppm with the same absorption chamber (5 cm length), where the measurement at very low concentrations is inaccurate (about 30 % at 50 ppm) and the sensitivity at very high concentrations is hundreds time lower (for 40 000 ppm than for 8 000 ppm). Therefore the measurements in particular concentration range can be also optimized by changing the length of the absorption cell.
Similar dependencies were also observed for other gases, particularly CH_4 and H_2O (see Fig. 8). The absolute value of the thermal voltage is very sensitive to the content of the gas mixture, to flow rate, temperature etc. Contrary to that the amplitude of the sine signal was

proportional only to the concentration of particular gas (depending on the optical filter) and was not dependent on the concentration of other gases. Of course, the absolute values of the absorption or sensitivity are different and depend on the optical filter and more generally on optical properties of the particular species of molecules. In our case, the CH_4 and H_2O exhibit significantly lower absorption. For example, 10 000 ppm CO_2 reduce the transmission of about 17 % (see Fig. 5). However 40 000 ppm CH_4 absorb only 7% of IR radiation (see Fig. 8). The lower measurable concentration of CH_4 was observed to be about 500 ppm, the standard deviation was about 120 ppm and the noise –about 600 ppm.

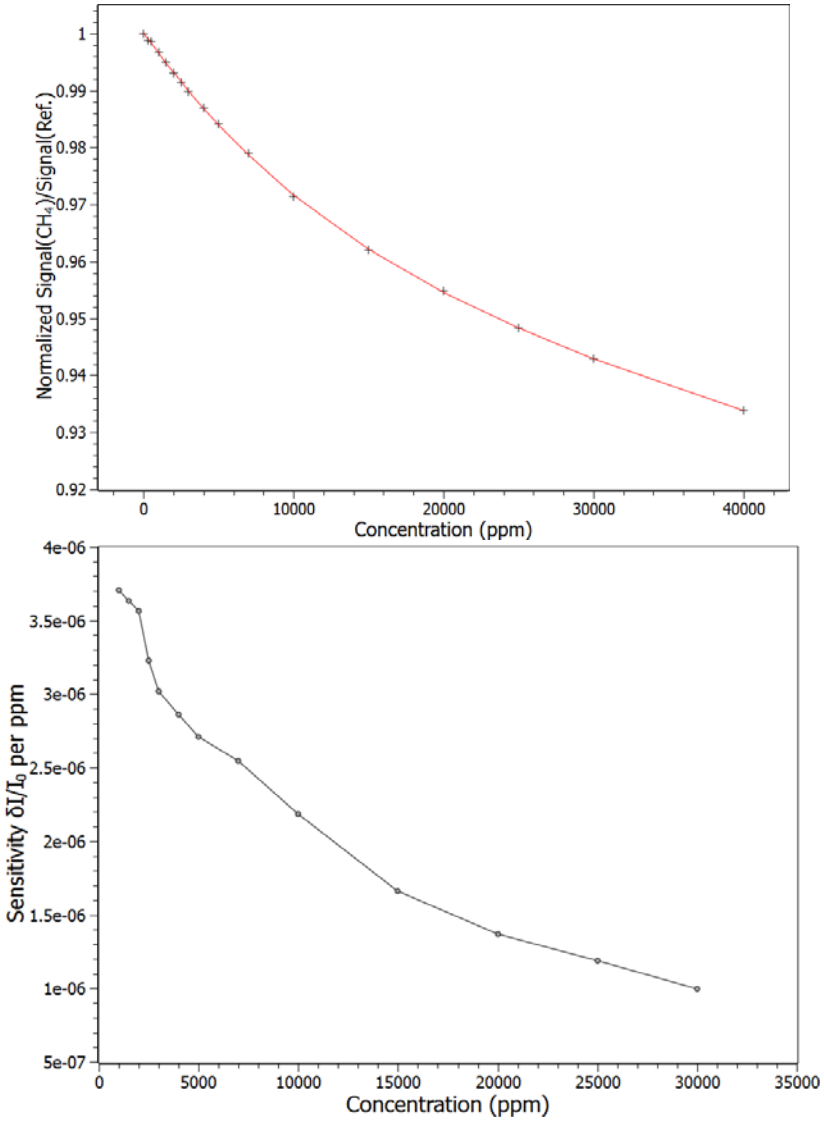

Fig. 8. Transmission and sensitivity of "CH_4" channel.

As it was mentioned above, some influence of the temperature change have been observed on the thermopile output signal. Fig.9 shows the thermal voltage of the same thermopile using different gas temperatures. Though the absolute value of the voltage is increasing with temperature (see Fig. 9b), the amplitude of the sine remains stable, and it was impossible to detect any amplitude changes in the temperature range between 15°C and 30°C.

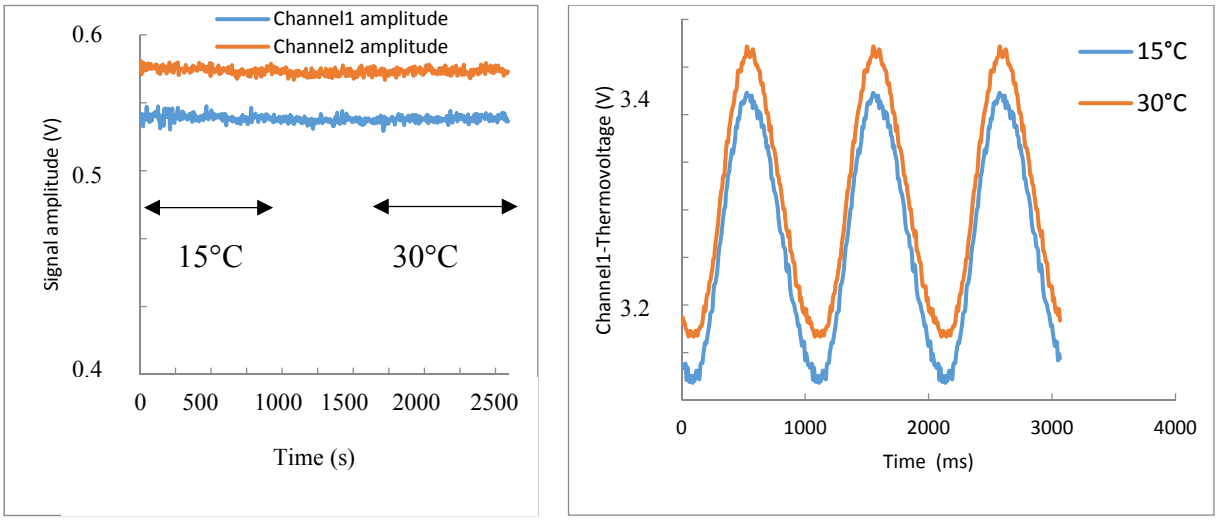

Fig. 9. The voltages of a thermopile at two different temperatures.

4. CONCLUSSIONS

The absolute thermopile voltages are not suitable for gas detection because of high sensitivity to the temperature and/or gas flow parameters. A sine like signal is preferential for the gas concentration measurement system. The amplitude of the sine is very stable and only proportional to the concentration of the particular gas (according to the optical filter) and is not dependent on the concentration of other gases or temperature. With the same measurement setup it was possible to measure CO_2 gas concentrations between 50 ppm and 400 000 ppm. The lower detectable concentration of CH_4 has been measured to be about 500 ppm.

5. ACKNOWLEDGEMENTS

This work was supported by German Federal Ministry of Education and Research (Nr. 16SV5284).

REFERENCES

[1] Y.L. Yang and Z.Y. Xie, “Design of indoor harmful gas monitor system”, Applied Mechanics and Materials, Trans Tech Publications, Vol. 423-426, pp. 2376-2379, 2013.

[2] N. Abatzoglou and S. Boivin, “A Review of Biogas Purification Processes”, Biofuels, Bioproducts and Biorefining, Society of Chemical Industry and John Wiley & Sons, Ltd, Vol. 3, pp. 42-71, 2009.

[3] S. Ashraf, C.G. Mattsson, G. Thungström and H. Rödjegård,” Integration of an interferometric IR absorber into an epoxy membrane based CO_2 detector”, Journal of Instrumentation, Vol. 9, Article number C05035, 2014.

[4] K.P. Yoo, H.P. Hong, M.J. Lee, S.J. Min, C.W. Park, W.S. Choi, N.K. Min, “Fabrication, characterization and application of a microelectromechanical system (MEMS) thermopile for non-dispersive infrared gas sensors”, Measurement Science and Technology, Vol.22, Article number 115206, 2011.

CONTACTS

Dr.-Ing. R. Mikuta Reinhard.Mikuta@ovgu.de