DOI 10.5162/SMSI2023/C3.4

Everything at once—Linearizing System Response and Enhancing Sensitivity in Photoacoustic Gas Sensors by Demodulation and Filter Tuning

Simon Essing[1], Gabriele Schrag[1], David Tumpold[2], Guillaume Dumas[2],
Andrey Kravchenko[3], Mohammadamir Ghaderi[2]
[1]Chair of Physics of Electrotechnology, Technical University of Munich, Germany,
[2]Infineon Technologies AG, Neubiberg, Germany,
[3]Infineon Technologies Dresden GmbH, Dresden, Germany
simon.essing@tum.de

Summary:

We present a sophisticated method to improve the sensitivity of CO_2-detecting non-resonant MEMS-based photoacoustic gas spectroscopy systems by more than 50 % compared to state-of-the-art approaches. The method based on signal demodulation can also be used to linearize the measured system's response in order to reduce the calibration effort for future sensors. Tuning the filter transmission spectra accordingly is utilized to further increase the linearity of the system response and enhancing the sensitivity by more than 200 %.

Keywords: algorithms, demodulation, linearization, photoacoustic spectroscopy, sensitivity

Background and State of the Art

Non-resonant miniaturized photoacoustic gas sensors (PAS) comprise a light source that often consists of a MEMS infrared emitter and an optical filter, a pressure chamber and a MEMS microphone[1]. Infrared Radiation is emitted and filtered in a way that the photons entering the pressure chamber match the wavelength needed to excite the gas molecules of interest. The excited molecules transfer the absorbed energy into an acoustical signal, which is detected by the microphone. State of the art systems currently used for CO_2 detection are prone to being cross sensitive to humidity [2, 3]. One major goal in sensor development is hence to provide maximum sensitivity to CO_2 while, at the same time, preserving robustness against changing environmental conditions such as humidity. A common signal analysis approach in this respect is to bandpass the microphone signal at the excitation frequency and calculate the root mean square (RMS) for every acoustical pulse, which is a measure for the gas concentration inside the pressure chamber and hence, the sensor's sensitivity [1, 4]. Our approach addresses the increase of this sensitivity w.r.t to the state of the art.

Description of the New Method or System

In an environment enriched with the target gas, the measured signal of the PAS is assumed to be a superposition of a CO_2- and a background-signal. The Microphone detects the transient pressure signal inside the chamber which is dominated by the excitation frequency of the emitter, see Fig. 1. Band-passing the signal at the excitation frequency suppresses interfering signal components leaving only the relevant signal content, see Fig. 2.

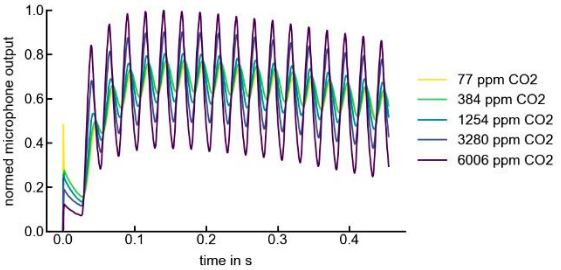

Fig. 1 Exemplary normed raw microphone output for various CO_2 concentration values.

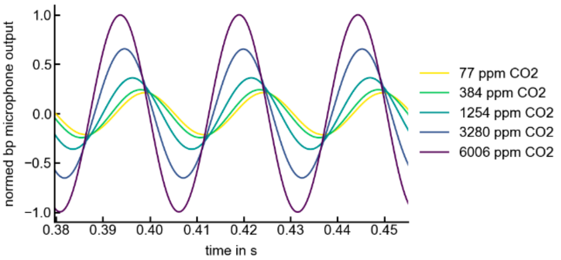

Fig. 2 Exemplary normed and band-passed microphone output showing the influence of increasing CO_2 concentrations on the overall phase and amplitude of the signal.

The basic idea behind the method is to demodulate the band-passed microphone signal into in-phase and quadrature components w.r.t to a specifically chosen phase angle, tailored to maximize the signal amplitude of the respective gas to be measured. Choosing a phase angle, which maximizes the signal of the CO_2 phase distinctly increases the sensor sensitivity compared to the pure RMS approach. The same can be done for any other target gas by adapting the phase to maximize this response. Additionally, by demodulating the signal w.r.t. the appropriate phase, the contribution of the CO_2 to the total signal becomes more pronounced and is also linearized for lower concentrations, as can be seen in Fig. ***3***.

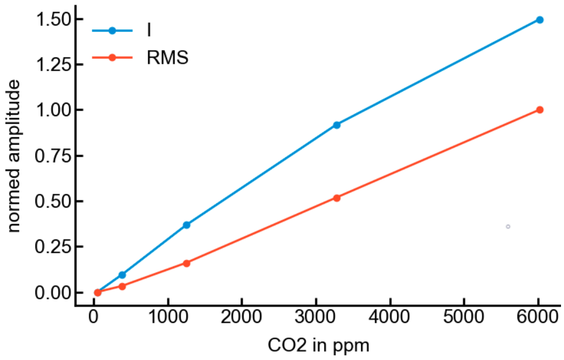

Fig. 3: Sensitivity gain of the “co2” filter to CO_2 by demodulating the microphone signal with a phase maximizing the CO_2 signal (signal “I”) compared to using the root mean square analysis of the microphone output (signal “RMS”). The amplitude, and thus, the sensitivity is increased by more than 50 %.

Experimental Results and Conclusion

Applying the described demodulation approach to measurements of our PAS system, a sensitivity increase of the amplitude of around 55% for CO_2 detection is achieved, while, at the same time, we attain linearization of the system response, especially for low concentrations. Additionally, the filter is designed in such a way that the system response to CO_2 is further increased compared to a typical CO_2 filter, see Fig. 4.

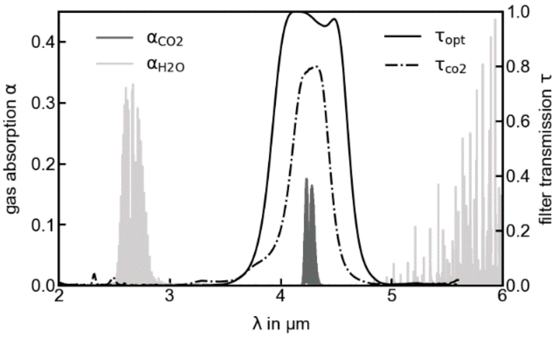

Fig. 4: Measured transmission spectra of optimized Bragg filters and the gas absorption spectra of water vapor and carbon dioxide. By expanding the transmission band for CO_2 an additional linear sensitivity of the demodulated sensor signal can be obtained, by still maintaining sufficient suppression of water bands to address cross sensitivity to relative humidity.

Fig. 4 shows the transmission spectra of a typical CO_2 Filter (“co2”) and the optimized filter (“opt”), increasing the absorption band relevant for CO_2 significantly. The depicted gas absorption spectra for H_2O and CO_2 are simulated by means of Lambert-Beer’s law for typical sensor dimensions under representative conditions ($p = 1013$ hPa, $T = 295$ K, $RH = 60\%$, $c_{CO2} = 420$ppm).

Hence, optimizing the optical filter increases the system response of the demodulated signals further by another 200% for the detection of CO_2, see Fig. 5).

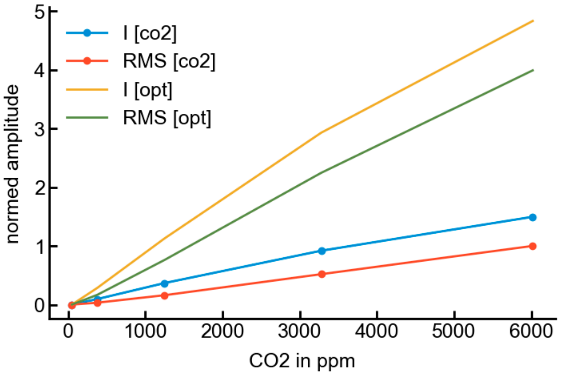

Fig. 5: Sensitivity gain of the optimized filter [opt] to CO_2 compared to the [co2] design by demodulating the microphone signal with a gain maximizing phase (signal I) compared to using a root mean square of the microphone signal (signal RMS). Optimization of the filter leads to a further increase in sensitivity by more than 200 %.

References

[1] S. Essing, G. Schrag, D. Tumpold, C. Glacer, M. Mihotek, and A. Kravchenko, “Towards predictive system-level modelling of miniaturized photoacoustic gas sensors,” in *2022 23rd International Conference on Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems (EuroSimE)*, St Julian, Malta, 4252022, pp. 1–5.

[2] S. Palzer, “Photoacoustic-Based Gas Sensing: A Review,” *Sensors (Basel, Switzerland)*, vol. 20, no. 9, 2020, doi: 10.3390/s20092745.

[3] S. Knobelspies, B. Bierer, A. Ortiz Perez, J. Wöllenstein, J. Kneer, and S. Palzer, “Low-cost gas sensing system for the reliable and precise measurement of methane, carbon dioxide and hydrogen sulfide in natural gas and biomethane,” *Sensors and Actuators B: Chemical*, vol. 236, pp. 885–892, 2016, doi: 10.1016/j.snb.2016.03.022.

[4] S. Gassner *et al.*, “Anodically Bonded Photoacoustic Transducer: An Approach towards Wafer-Level Optical Gas Sensors,” *Sensors (Basel, Switzerland)*, vol. 22, no. 2, 2022, doi: 10.3390/s22020685.