**Compact photoacoustic gas sensor based on broadband IR source**

Katrin Schmitt\textsuperscript{a,}*, Andreas Müller\textsuperscript{a}, Jochen Huber\textsuperscript{a}, Sebastian Busch\textsuperscript{b}, Jürgen Wöllenstein\textsuperscript{a,b}

\textsuperscript{a}Fraunhofer Institute for Physical Measurement Techniques, Heidenhofstr. 8, 79110 Freiburg, Germany
\textsuperscript{b}University of Freiburg, Department for Microsystems Engineering IMTEK, Georges-Köhler-Allee 102, 79110 Freiburg, Germany

**Abstract**

We present the realization of a novel, compact IR-optical gas sensing system based on photoacoustic detection. A modular detection cell in combination with a long-path cell allowed the detection of CO\textsubscript{2} and ethylene (C\textsubscript{2}H\textsubscript{4}) using a broadband IR source (thermal emitter). The system performance was investigated both in simulations and experiments using CO\textsubscript{2} and ethylene as target gases. The experimental results were in good accordance with the simulation results. We aimed at the integration of low-cost components and the miniaturization of the complete system to open up the possibility for sensor networks. Furthermore, the modular detection cell allows the optimization of the optical path length within the measurement cell and thus the adaptation to different target gases.

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*Corresponding author. Tel.: +49-761-8857-316; fax: +49-761-8857-224.
E-mail address: katrin.schmitt@ipm.fraunhofer.de

**1. Introduction**

CO\textsubscript{2} and C\textsubscript{2}H\textsubscript{4} are two major target gases to be monitored in greenhouses. Testing of CO\textsubscript{2} is essential to maintain the optimum growth conditions for plants, while ethylene monitoring is important in greenhouses powered from adjacent cogeneration power stations (combined heat and power, CHP). Today greenhouses are often equipped with adjacent CHP power stations for economical reasons. Yet during ventilation of the greenhouses, exhaust gases from the power station, among them a high concentration of ethylene, enter the greenhouse. High concentrations of ethylene lead to faster and uncontrolled ripening of the fruits, thus ethylene monitoring in greenhouses with adjacent CHP power...
stations is crucial. Photoacoustic spectroscopy allows the fast and sensitive detection of \( \text{CO}_2 \) and ethylene, yet to date a low-cost and compact system suitable for use in depots and containers is not available. Several approaches for ethylene monitoring by photoacoustic gas detection exist [1,2]. Yet in most cases they are too expensive and complex since they rely on laser light sources [3,4]. We present the development of a low-cost and compact photoacoustic gas sensor system for the fast detection of \( \text{CO}_2 \) and ethylene.

2. Experimental

2.1. Photoacoustic detection of \( \text{CO}_2 \) and ethylene

Photoacoustic detection makes use of the fact that gas molecules absorb light of a specific wavelength in the infrared and convert it into kinetic energy. The relaxation of the excited state causes an increase in the kinetic energy in the gas and therefore a rise in temperature. The increased temperature leads to a thermoelectric expansion of the gas, i.e. an increasing pressure. In the same way, the pressure drops when infrared radiation is absent. When an infrared emitter is used, modulated at a frequency \( \omega \), in combination with a suitable microphone, small pressure variations can be detected (typically around \( 10^{-2} \) to \( 10^{-1} \) Pa).

The heat production rate \( H(\omega) \) is a function of the absorption coefficient \( \alpha \) and the intensity of the emitter \( I_0 \). Many molecules show a characteristic absorption in the infrared. Dependent on the molecule structure and the incident radiation energy, we obtain absorption bands at distinctive wavelengths. Fig. 1 shows the absorption bands of \( \text{CO}_2 \) between 4 and 5 \( \mu \text{m} \) (Fig. 1a) and ethylene between 8 and 13 \( \mu \text{m} \) (Fig. 1b).

![Fig. 1. (a) Infrared transmission spectrum of \( \text{CO}_2 \) between 4\( \mu \text{m} \) and 5\( \mu \text{m} \) (100\%, 1 m optical path length). (b) Infrared transmission spectrum of ethylene between 8\( \mu \text{m} \) and 13\( \mu \text{m} \) (100\%, 1 m optical path length). Source: HITRAN](image)

2.2 Sensor design

The formation and amplitude of the alternating pressure and the wave propagation is described by acoustic sound equations. These equations have resonant and non-resonant solutions. The photoacoustic pressure signal for the non-resonant case is a function of the radiation power \( I_0 \), the modulation frequency \( \omega \), the absorption coefficient \( \alpha \) and the adiabatic coefficient \( \gamma \). For the design of the system, these parameters were used to estimate the pressure amplitude (Fig. 2a). An important parameter is a suitable modulation frequency, which was (for ethylene) determined using a measurement cell filled with 100% ethylene. The variation of the modulation frequency between 10 and 70 Hz, an exponential decay of the
A pressure signal could be observed with increasing frequency. A low modulation frequency thus leads to a better detection limit. Fig. 2b shows a photograph of the modular photoacoustic cell including connectors.

![Fig. 2b Photograph of modular photoacoustic cell including connectors.](image)

**3. Results**

In a first step the target gases CO\(_2\) and ethylene (both 100\%) were measured using a commercially available photoacoustic cell (PAS Analytik GmbH, Germany) and an IR emitter at the same power. Fig. 3 depicts the resulting signal curves. The amplitudes are almost equal for both gases, yet the signal curve shapes are different during the decay phases: for ethylene, the slope is quite steep and almost linear compared to CO\(_2\). To obtain better detection limits, the modular detection cell was optimized and integrated together with a multi-reflection cell into the setup. In addition, the microphone and the preamplifier had to be replaced to obtain good results at a modulation frequency of 15 Hz. Fig. 4 shows a test of the system using N\(_2\) as buffer gas. Ethylene was measured at 3.3\% and 4.9\% (in N\(_2\)). From the signal curves for these concentrations, a detection limit of ~1\% ethylene can be deduced.

![Fig. 4 Test of system using N\(_2\) as buffer gas.](image)

**Fig. 2.** (a) Estimation of the pressure amplitude for a measurement cell (l= 100 mm, d = 15mm) filled with 100 \% ethylene. A modulation frequency of 15 Hz and an emitter temperature of 1173 K result in pressure amplitudes around 0.02Pa. For comparison: non-active gas in the infrared results in pressure amplitudes around 0.007Pa, with 1\% ethylene: 0.006Pa.

(b) Modular photoacoustic cell including connectors for filling the cell with target gas.

![Fig. 3 Signal curves.](image)

**Fig. 3.** (a) Signal amplitudes for 100\% CO\(_2\), alternating with buffer gas (N\(_2\)) (b) Signal amplitudes for 100\% ethylene, alternating with buffer gas (N\(_2\)).
4. Conclusions and Outlook

We realized a photoacoustic gas detection system using a broadband IR emitter. The system characteristics (pressure amplitudes at different concentrations, dependency of pressure amplitude from modulation frequency) were simulated and are in good accordance with the experimental results. The system was tested with CO₂ at 4.3 µm and ethylene at 10.6 µm. CO₂ could be detected in very low concentrations (< ppm) even without the long path cell. The detection limit for ethylene was found to be around 1%. The high detection limit has several reasons: the IR source, having blackbody characteristics, emits only weakly in the wavelength range around 10.6 µm. The detector unit was not optimized for the modulation frequency of 15 Hz. This will be improved in next steps through optimization of the signal-to-noise ratio using IR emitters at higher temperatures and microphones and preamplifiers better suited for low modulation frequencies. A further improvement will be the miniaturization of the setup through optimized multi-reflection cells.

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