

Trace Level Moisture Sensing using a Resonant Photoacoustic Sensor with an LED as Light Source

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Summary:

Measuring the water content of gas mixtures is relevant in a large variety of industrial applications ranging from pressurized air to energy or process control applications. Here we present a novel photoacoustic sensor design that uses a LED with a wavelength of 2.7 μm and a radial resonator to achieve detection limits in the single-digit ppm region at averaging time of over 20 seconds. An 8-hour zero-gas measurement shows no drift over this period, enabling even lower detection limits with high averaging times.

Keywords: Photoacoustic, Resonant, LED, Water Sensing, Optical

Motivation

Trace-level moisture sensing is essential in a large variety of industrial applications [1]. Even very low water vapor concentrations in the low ppm to ppb range can cause damage to the productions equipment and reduce product quality in the semiconductor and chemical industries. Therefore, reliable detection methods are required for early detection of faulty conditions resulting in equipment failures, product recalls, and safety hazards while optimizing overall efficiency of processes.

Currently, trace level moisture is measured using a number of various methods that are either very complex (e.g. laser-spectrometers, dew point mirrors) or have slow response times are prone to drift and contamination, like capacitive sensors or quartz resonator sensors [2].

We present an LED driven photoacoustic (PA) moisture sensor that can bridge the gap between both technologies and provide a drift-stable sensing method with low sensor complexity.

Photoacoustic Sensor Design

High power LEDs are usually large and have an area of at least 1 mm². To guide a significant fraction of the light through a photoacoustic cell without wall interaction, a large cell aperture is necessary. The sensor presented in this work fulfills this requirement with a cylindrical resonator of 20 mm length and 8 mm length. The light of a mid-IR led with 2.7 μm peak wavelength and 3 mW optical power (nanoplus, Germany) is collimated by a parabolic mirror and a f=35 mm CaF₂ lens and then guided along the cylinder's axis through the cell. A silver-plated concave

mirror (f=50 mm) at the outlet focuses the radiation back into the cell for a second pass. This concentrates the radiation intensity at the center of the cylindrical cell, leading to a high overlap integral with the first radial resonant mode. The radial mode also has a large Q-factor, making it ideal for photoacoustic measurements. With the dimensions of the cell, it is located around 21 kHz in air. The whole assembly, which is made of aluminum (see Fig. 1), has diameter of 48 mm and a length of 92 mm.

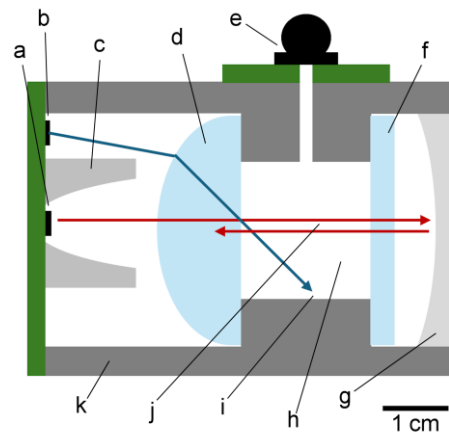


Fig. 1. Simplified drawing of the Sensor setup: a) MIR-LED, b) tracking-LED, c) reflector, d) 35 mm CaF₂ lens, e) microphone, f) outlet CaF₂ window, g) concave mirror, h) resonant photoacoustic cavity, i) wall absorption providing a reference signal, j) photoacoustic signal generation in two passes, k) housing

The acoustic signal is acquired by a MEMS microphone (SPV61A0L, Knowles, USA), amplified by a factor of 110 and bandpass filtered. It is then digitalized at 1 MSa/s and filtered by a point-by-

point FIR lock-in filter running on a PSoC6 (Infineon, Germany) based embedded system. The system also incorporates an LED driver and transmits the measured data to a host PC via USB. The resonance frequency is tracked by a second LED with 850 nm wavelength using the method described in [3].

Results and Discussion

The sensor was characterized in a gas measurement laboratory to determine its sensitivity and linearity. The time constant of the filter was set to 2 s and the LED was driven with 200 mA peak-to-peak. Relative humidity steps of 0 to 10% at 22°C at a flow rate of 0.1 l/min were applied to the sensor. The recorded measurement is shown in Fig. 2.

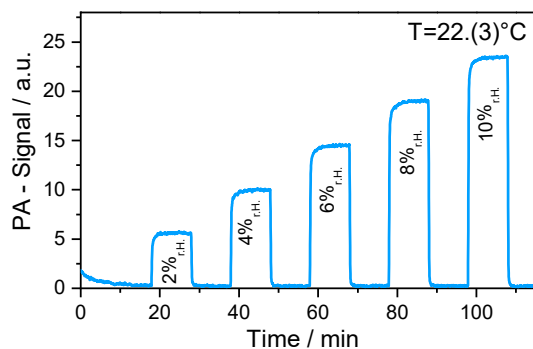


Fig. 2. Sensor response towards steps of 2 to 10% relative humidity in dry nitrogen.

Due to the low inner volume, the measurement values settle down with a time constant of approx. 2.4 s. A second time constant can be observed, that can probably be attributed to the water saturation of the sensor cell. All applied concentrations can clearly be resolved and no deviations in the nitrogen steps are observable, aside from the initial drop from ambient moisture. For a better evaluation of the linearity Fig. 3 shows the magnitude of each step along with the respective standard deviations. Typical for a PA sensor, the linearity is better than the noise in the system. A fit in Fig. 3 emphasizes this. The fit does not meet the Y-axis at 0 but rather at 1.25

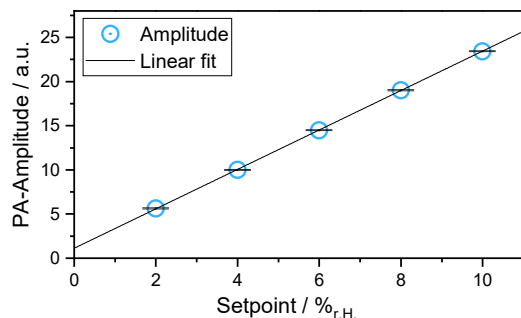


Fig. 3. Measured PA amplitude vs. Setpoint humidity together, along with the standard deviation of the steps. A fit emphasizes the sensor's linear behavior.

counts, which is also more than the offset in Fig. 2. This is likely caused by a systematic offset of the mass flow controller in the open state rather than being an actual measurement effect.

For the evaluation of the detection limits and noise, the sensor signal was recorded for 8.5 h with dry nitrogen applied. Fig. 4. shows the result together with the Allan deviation calculated from it. The sensor signal was calibrated by a 1-point factor extracted from the 10%_{r.H.} step (2650 ppm) from the previous measurement.

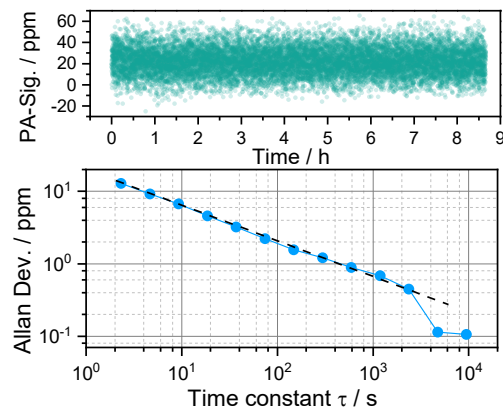


Fig. 4. Zero signal over a period of 8.5 h and the Allan deviation calculated from it. The dashed line indicates the slope of white noise.

The Allan plot shows no drift limitation over the observed time interval. Over a wide range of averaging times, the Allan deviation decreases by 10dB/decade indicating white noise. The noise equivalent concentrations are 12 ppm at 2s, 2 ppm at 60 s and 800 ppb at 1000 s. These correspond to noise equivalent dew points of -65°C, -72°C and -83°C.

These results demonstrate that photoacoustic sensing using mid infrared LEDs can provide a reliable and low-drift measurement of moisture down in the low ppm to the high ppb range. The sensor design can furthermore be compact and of low complexity.

References

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