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A humidity-independent photoacoustic sensor

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Summary:
Photoacoustic spectroscopy is routinely used to characterize absorption of gas and aerosols in various environments. To obtain accurate absorption measurements in atmospheric science, where variations in humidity exist, the photoacoustic signal's dependence from relative humidity must be investigated in-depth. For this purpose, we used a resonant photoacoustic cell embedded with a piezoMEMS microphone, which is insensitive to humidity. We scanned the light modulation frequency around the theoretical resonance value and acquired the microphone signal through a lock-in amplifier. From the results, we can affirm that the overall photoacoustic sensor response is independent of the humidity parameter only if we consider the photoacoustic signal amplitude at the exact resonance frequency, which shifts with humidity.

Keywords: photoacoustic effect, piezo MEMS, QCL laser, relative humidity, post-processing signal.

Introduction

Photoacoustic spectroscopy (PAS) is a technique based on the optical absorption of modulated light by solids, liquids or gases. The absorption leads to thermal expansion of the absorber at the modulation frequency of the light ("photo"), causing a pressure wave to be formed and detected by an acoustic transducer ("acoustic") (Fig.1) [1]. Gases or aerosols samples are commonly confined inside an acoustically resonant photoacoustic cell for measurement, and the resulting sound wave intensity is directly proportional to the amount of those absorbers. Therefore, PAS is routinely applied for absorption measurements in atmospheric science.

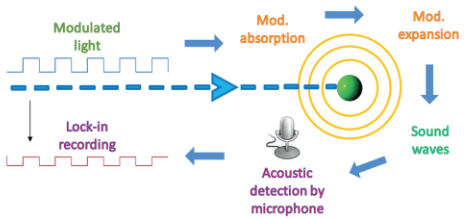

Fig. 1. Representation of the photoacoustic principle

The goal of our research is to improve the fundamental understanding of the PAS signal generation process and its dependence on atmospheric parameters. In this paper, we investigate whether a humidity-insensitive photoacoustic sensor can be developed with a piezoMEMS microphone. We tested the efficiency of the PAS sensor to measure ethanol absorption at varying humidity levels.

Methods and Materials

The experimental setup consists of a PAS cell with a piezo MEMS PMM-3738-CM1000-R microphone positioned in the center of the 4 cm long resonator (Fig 2). While electret microphones are commonly used in PAS cells, these are sensitive to humidity [2]. Therefore, we chose a microphone with a humidity-insensitive piezoelectric crystal in the piezo MEMS.

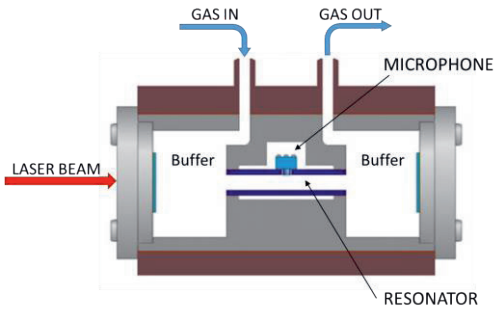

Fig. 2. Resonant photoacoustic cell with resonator and buffer volumes used in this study.

The sample is excited by an intensity-modulated QCL at 9.47 µm. Ethanol vapor was used as the absorbing sample due to its strong absorption in the infrared range. We used nitrogen as carrier gas, and the gas mixture was humidified by flowing through the headspace of a flask filled with distilled water. Different relative humidity (RH) levels were reached by dilution with dry nitrogen. RH was measured with a sensor (HYTE-ANA10V) at the inlet of the PAS cell. The ethanol concentration of was measured with a FTIR spectrometer (Fig.3).

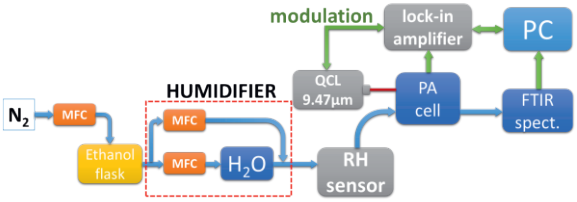

Fig. 3. Scheme of the experimental setup. MFC – mass flow controller.

The presence of water in the sample leads to a change of speed of sound of the gas sample and, consequently, to a shift of the resonance frequency. To identify the exact resonance peak at different RH values, the laser modulation frequency was swept from 3.9 to 4.2 kHz. Photoacoustic (PA) signals were measured for RH levels from 1% up to 50%.

Results

In Fig. 4, curves with red shades depict PA signals detected at low RH (1-22%), while blue curves represent higher RH (30-50%). The signals at the exact resonance peak are marked with red diamonds, and are shifted to higher frequency with increasing RH. This is in agreement with the change of the speed of sound in gas mixtures in the presence of humidity [3]. Moreover, a variation of the signals amplitudes is observed, because of variations in ethanol concentration at different RH levels.

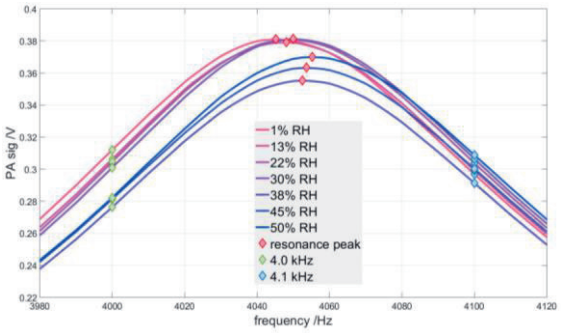

Fig. 4. Photoacoustic signal acquired sweeping the frequency at different relative humidity.

We analyzed the PA signal measured at three different modulation frequencies (marked in Fig. 4): the shifting peak resonance frequency (red diamonds), a fixed f = 4.0 kHz (green diamonds), and a fixed f = 4.1 kHz (blue diamonds). A plot of the PA signal as a function of ethanol concentration at each of these frequencies is shown in Fig. 5 (data points). For comparison, we also show the PA signal vs. ethanol concentration, measured under dry conditions at the three specified frequencies (solid lines).
The PA signal measured at the exact resonance frequency peak at different level of humidity (red points) are consistent with the calibration curve at dry conditions for all concentrations of ethanol.

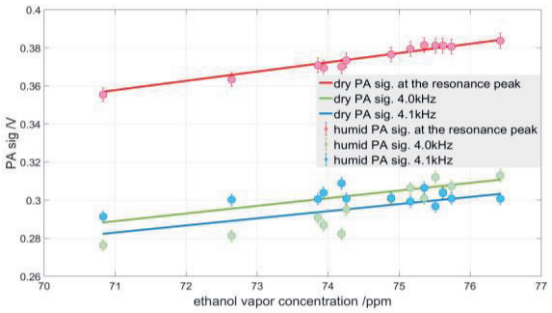

Fig. 5. Amplitude of the photoacoustic signal in humid conditions compared to the calibration curves obtained in dry conditions.

The results indicate that at the condition of ideal resonance, the signals measured from our PAS sensor are insensitive to changes in RH, and all variations in amplitude are attributed to changes in absorber concentration. On the other hand, data acquired at a fixed frequency, which is typically done in PAS measurements, show a deviation between the dry calibration line and the humid sample measurements, as shown by our data at f = 4.0 kHz (green) and f = 4.1 kHz (blue). Measuring the PA signal at a fixed modulation frequency, therefore, could create an apparent dependence of the signal on humidity.

Conclusion

We investigated PA signals generated at different humidity conditions. PA signals were shown to be completely independent from humidity in exact resonant conditions. Future applications of this work include studying the humidity dependence of the PA signal generation from aerosols. In particular, in the case of hygroscopic particles, light absorption leads to not only the formation of pressure waves but also a partial evaporation of volatile compounds and water, and a humidity-insensitive PAS sensor is needed to quantitatively study this behavior.

References

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