

# Real-time resonance tracking for acoustic resonator enhanced photoacoustic gas sensors

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## Summary:

Trace gas detection is crucial for environmental monitoring and numerous industrial applications. Direct photoacoustic is a promising technique for reliable gas sample analysis and their performance may be improved by employing acoustic resonators to enhance sensitivity. However, changes in gas conditions alter both resonance frequency and quality factor, making robust, long-term stable operation challenging. Here a locking scheme for real-time tracking based on a frequency modulation scheme is presented. Inspired by Pound–Drever–Hall locking, the method exploits the resonator's phase response and enables fast, stable PAS measurements in a lean implementation.

**Keywords:** trace gas sensing, photoacoustics, acoustic resonators, resonance tracking

## Introduction

Direct photoacoustic spectroscopy (PAS) is a powerful method for selective trace-gas detection. In order to enhance sensitivity, PAS systems often employ acoustic resonators to amplify the light-induced acoustic wave, where the optical modulation frequency is matched to an acoustic eigenmode. The resulting resonant amplification significantly increases the photoacoustic signal amplitude and consequently improves sensitivity and the limit of detection [1].

Nonetheless, long-term stability hinges on accounting for fluctuations of the exciting light intensity as well as tracking the resonator properties. Since the signal strength scales approximately with the quality factor  $Q$ , it is paramount to reliably determine this quantity in order to relate the recorded acoustic signal strength to the target gas concentration. In practical sensing conditions the thermophysical properties of the gas are altered by variations in gas composition, concentration, pressure, or temperature, leading to shifts in the acoustic resonator's resonance frequency  $f_0$  and changes in the  $Q$ -factor. To this end, locking schemes to track both the  $Q$ -factor and the resonance frequency are necessary for long-term stable operation of PAS sensors. Methods to achieve this include point-by-point frequency scanning [2], chirped modulation [3], light-induced wall signal techniques [4], and transient heterodyne excitation [5].

While these approaches can track the resonance frequency, they increase system complexity or require complex setups. Here an active locking scheme for real-time tracking of the resonance frequency and determination of the  $Q$  factor based on mixing three modulation frequencies is presented. It does not require frequency sweeping, which enables fast, real-time tracking of the acoustic eigenmode and gas concentration determination.

## Method

The scheme is akin to the Pound-Drever-Hall laser locking scheme [6] and relies on the phase shift acoustic signals experience when interacting with acoustic resonators. To implement the scheme, a carrier frequency, which in this case is the modulation frequency  $f_c$  to excite photoacoustic signals is accompanied by two sidebands located at  $f_{-1,+1} = f_c \pm f_m$ , where  $f_m$  is the sideband modulation frequency. Depending on the respective position with respect to the frequency of the resonator eigenmodes, each frequency experiences an individual phase shift. By comparing the amplitude and the phase of the signal originating from the two sidebands, an error signal may be generated to determine and adjust  $f_c$ .

## Experimental

In order to demonstrate the approach a cylindrical, open resonator with inner diameter of  $d = 5$  mm and a length of 55 mm is employed. An analog MEMS microphone (IvenSense ICS-40619)

is mounted at the back wall and its signal is amplified using a low noise circuit prior to digitization via a differential amplifier circuit with band-pass filter, containing operational amplifiers (Analog Devices LT6235). Control of the sound source, determination of the amplitude and phase of the microphone signal and calculation of  $f_c$  and Q-factor, respectively, is embedded in a PSoC 5 microcontroller. The microcontroller generates a composite waveform consisting of the carrier frequency at  $f_c$  and the two sidebands and outputs that signal via its internal DAC to an amplifier which drives the capacitor. Simultaneously the lock-in values are calculated by using the microphone signal digitalized by the internal ADC. A new carrier frequency is estimated from the calculated amplitudes and phases measured at the carrier frequency and the sidebands.

Figure 1 depicts the schematic setup. To demonstrate the approach a ceramic capacitor (10  $\mu$ F, X7R, 1206, Kemet C1206C106K4RAC7800) is used to excite acoustic waves.

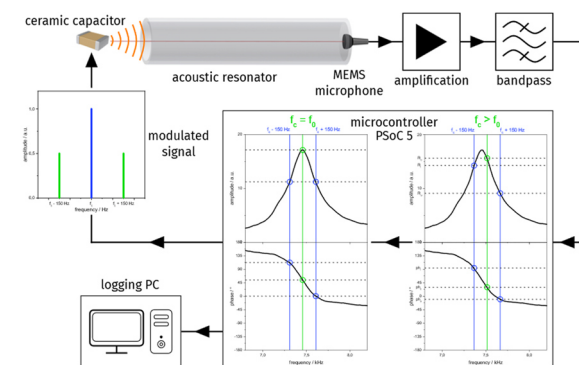


Figure 1: The figure shows the schematic setup. The microcontroller corrects the carrier frequency  $f_c$  to fit the resonance mode of the resonator.

## Results

A frequency sweep in the range from 1 – 20 kHz confirms the location of the longitudinal eigenmodes and the amplitude as determined by

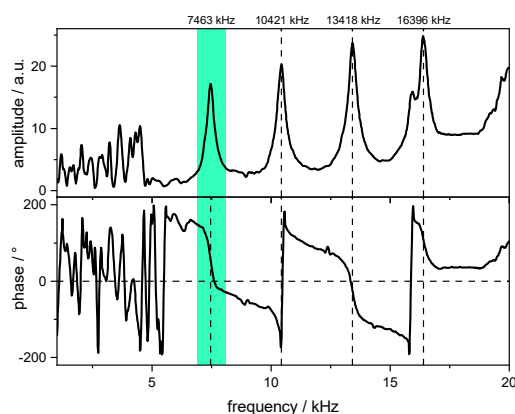


Figure 2: Determined amplitudes and phases by the lock-in algorithm when outputting a frequency sweep from 1 kHz to 20 kHz.

the lock-in algorithm along with the phase between modulation source and microphone signal are depicted in Figure 2. By mixing the signals originating from the sidebands both the error signal and the Q-factor are extracted. Figure 3 shows the results of the determination of resonance frequency for varying temperature, and gas composition. The characterization has been performed in a controlled environment.

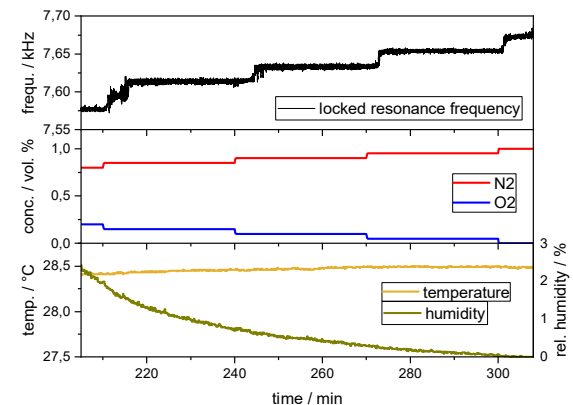


Figure 3: The plot shows the automatically locked resonance frequency for changing gas concentrations.

## Conclusion

The use of three frequency modulation of sound sources to excite acoustic resonators enables the real-time determination of both the resonance frequency and the Q-factor, which in turn allows for stable and continuous real-time concentration measurements in direct photoacoustic setups. The speed of resonance tracking is limited only by the sampling rate of the ADC and consequently allows for establishing long-term stable operation without the need for adding complexity to the direct photoacoustic setup. The scheme is scalable in the sense that various eigenmodes of the resonator may be tracked simultaneously.

## References

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