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Photoacoustic gas sensing employing an improved radial resonator

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Abstract: We present a novel configuration for photoacoustic gas sensing demonstrating QEPAS state-of-the-art sensitivity, while allowing coupling with possibly divergent or multipoint sources. This configuration was simulated and characterised experimentally. © 2023 The Author(s)

1. Motivation

Photoacoustic spectroscopy is a wavelength independent detection method for trace gas detection down to parts per billion (ppb), enabling the use of virtually any light source, thus constituting a strong multi-gas and cost effective solution [1].

Besides microphones [1] and cantilevers [2], quartz tuning forks (QTF) can also be employed in photoacoustic spectroscopy [3]. These resonators are used at their resonance frequency (usually 1 kHz to 40 kHz), and exhibit a strong quality factor (usually several thousands at atmospheric pressure).

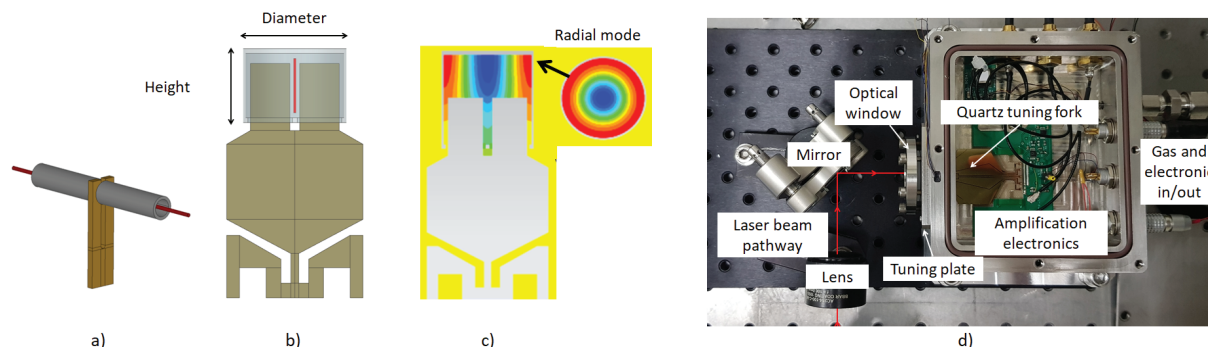


Fig. 1. (a) Scheme of a watch QTF in "on-beam" configuration. (b) Scheme of our new configuration in which the laser beam is parallel to the QTF prongs and the symmetry axis of the acoustic resonator. (c) Acoustic simulation showing the radial mode of the resonator (d) Fabricated sensor inside a gas hermetic cell.

To enhance their sensitivity to acoustic waves, QTFs are coupled to acoustic resonators, usually under the form of metallic tubes in which the laser beam passes [4] (see Fig. 1). This configuration called "on-beam" enables to reach state-of-the-art sensitivity, quantified by a normalised noise equivalent absorption (NNEA) of $\sim 1 \cdot 10^{-9} \text{ cm}^{-1} \cdot \text{Hz}^{-1/2}$. However, focusing the laser beam inside those tubes of diameter less than 1 mm and 1 cm length is difficult and generates a background signal, but also strongly degrades the instrument multi-gas capacity. To circumvent these drawbacks we presented the first radial acoustic resonator used in quartz enhanced photoacoustic spectroscopy (QEPAS) [5], exhibiting a NNEA of $3.9 \cdot 10^{-9} \text{ cm}^{-1} \cdot \text{Hz}^{-1/2}$. This acoustic resonator well coupled to a custom QTF, enables to focus the laser beam in a $\sim 2 \times 2 \text{ mm}^2$ area, thus relaxing alignment constraints compared to the on-beam configuration. Here we present an improvement of this configuration, allowing to reach a near tenfold sensitivity enhancement (see Fig. 1) while being able to focus the laser beam outside of the QTF prongs.

2. Method

In order to maximise the sensitivity, the configuration was changed from "on-beam" to "in-plane" [3] increasing the laser beam interaction length with the gas as well as the overlapping between the acoustic mode and the QTF. The slits present in the acoustic resonator necessary for QTF insertion were reduced in order to reduce acoustic

losses.

This configuration was investigated and the NNEA was minimised by thorough finite element simulations combined with analytical modelling. The radial resonator radius was fixed to 10 mm and its height was varied in order for its frequency to match the QTF one. We found a theoretical sensitivity optimum of $8 \cdot 10^{-10} \text{ cm}^{-1} \cdot \text{Hz}^{-1/2}$, close to QEPAS experimental state-of-the-art, for a resonator height of 13 mm. It is interesting to note that the maximal sensitivity does not occur for a quality factor minimum as it had always been the case in literature for classic configurations such as "on-beam" [4].

We then designed and fabricated this new configuration as shown in Fig. 1. The QTF was placed inside a stainless steel gas cell with its signal amplification electronics. The signal was fed to a commercial lock-in amplifier.

3. Experimental results

This new configuration was characterised on our reference photoacoustic bench, that uses a pigtailed single-longitudinal-mode DFB telecom diode and a fibered Mach-Zhender for amplitude modulation and a current driver for wavelength modulation. We targeted C_2H_2 at a 1000 parts per million concentration (ppm) in N_2 at atmospheric pressure at the 6490.02 cm^{-1} absorption line (corresponding to 5550 \AA in Fig. 2). A laser beam double pass was implemented thanks to a thin gold mirror put in the back of the radial resonator. The laser beam was focused between the QTF prongs (space of 2 mm) thanks to a 100 mm focal lens, and presented a waist of 45 \mu m at the mirror plane.

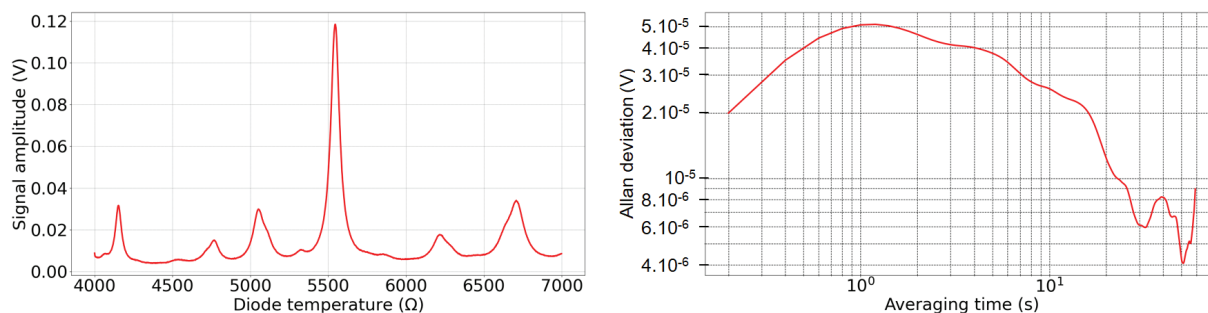


Fig. 2. (Left) Measured absorption spectrum of C_2H_2 using amplitude modulation. (Right) Overlapping Allan-Werle deviation of the signal.

We thoroughly studied the coupling between the QTF and the acoustic resonator by varying the radial resonator height with tuning plates of different thicknesses. The optimal sensitivity was found for a total height of the radial resonator of about 22 mm. At this optimum, the detector exhibits a frequency of 21,434 Hz and a quality factor of 13,800. The sensitivity was calculated from the signal and Allan-Werle (see Fig. 2)) deviation to be $5 \cdot 10^{-10} \text{ cm}^{-1} \cdot \text{Hz}^{-1/2}$, representing an enhancement of a factor nearly 8 compared to our previous configuration and reaching QEPAS state-of-the-art sensitivity. Such a detector enables a strong multi-gas potential by allowing the use of possibly divergent or multi-point sources, while exhibiting a very good sensitivity, paving the way towards multi-gas and cost-effective sensors.

We are currently working on the implementation of this detector for multi-gas sensing by integrating it into a single instrument with several quantum cascade laser arrays.

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