

A new QEPAS sensor optimized for the use of multiple optical sources with reduced window absorption

Ilona Troadec¹, Maxime Duquesnoy¹, Jean-Michel Melkonian¹, Raphaël Levy¹, Myriam Raybaut¹

¹ ONERA, 6 Chemin de la Vauve aux Granges 91120 Palaiseau, France

ilona.troadec@onera.fr

Summary :

The development of sensitive, selective, multi-gas, fast and compact sensors to detect and identify polluting or toxic gases is a key challenge for public, industrial and military safety. We present a quartz-enhanced photoacoustic spectroscopy (QEPAS) sensor using a custom quartz tuning fork coupled to an acoustic resonator. The design was optimized with finite element method (FEM) and adapted for an optical multi-pass of laser arrays. It was validated experimentally by measuring C₂H₂, showing the expected acoustic mode, the reduction of window background and a sensitivity of $1.10^{-8} \text{ W.cm}^{-1}.\text{Hz}^{-1/2}$.

Keywords: Gas sensors, photoacoustic, spectroscopy, quartz, resonator

Context

The detection of greenhouse gases, toxic industrial chemicals (TICs) and chemical warfare agents (CWAs) has been identified as a major challenge for the public, industrial and military safety [1]. It has become necessary to develop compact, sensitive (ppbv level to reduce exposure), selective (to avoid interference), multi-gas (to cover more threats) and fast sensors [2]. Photoacoustic spectrometry is based on optical absorption of laser light by the rovibrational modes of molecules. When the molecular gas is periodically excited by a modulated light, acoustic waves are created and later detected by a mechanical resonator (microphone, tuning fork, cantilever...) [3]. Photoacoustic spectroscopy presents a good selectivity and could fulfill the mentioned applications requirements [4,5]. However, some challenges remain. Harmful gases and many pollutants have complex molecular structures and thus present large optical absorption spectrum features ($\sim 100 \text{ cm}^{-1}$) in the mid-infrared region (3-14 μm). To probe these features, quantum cascade laser arrays (QCL) or Interband Cascade Lasers (ICL) that are widely wavelength-tunable or incorporate several emitters at different wavelengths are essential. Also, periodic excitation of the absorption features is only effective with amplitude modulation, in contrast to wavelength modulation. These requirements strongly constrain the geometry of the opto-acoustical coupling and require a specific conception, which we patented [6] and describe in the next section.

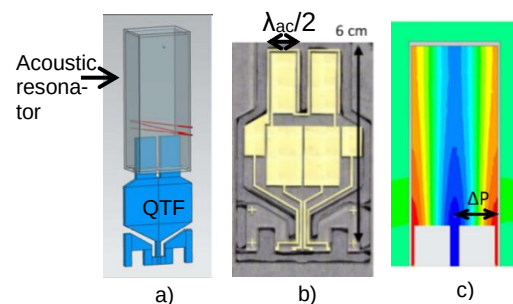


Fig. 1. a) CAD model of the sensor. b) Picture of the custom QTF. c) Simulation of the acoustic mode at resonance frequency (Red and blue: extrema of pressure with opposite phases. Green: pressure node)

New Sensor Design

A prototype using a quartz tuning fork (QTF) coupled with an acoustic resonator (fig.1a) has been designed and optimized through finite element method (FEM) simulations. The custom QTF (fig.1b) is dimensioned to be strongly coupled to an acoustic wave. Its prong width equal to half the acoustic wavelength $\lambda_{ac}/2$ was chosen in order to maximize the pressure amplitude between external and internal QTF faces. The QTF resonates at f_0 around 17450 Hz, resulting in an acoustic wavelength of 19.6 mm in air. The rectangular acoustic resonator is designed to present an acoustic mode adapted to maximize the pressure delta ΔP between the prongs (fig.1c). This maximizes the displacement of the prongs, i.e. the signal-to-noise ratio. Also, by design, the chosen acoustic mode presents pressure nodes (in green in fig. 1c) where the laser beam can enter and exit diagonally the resonator to minimize the background signal created by optical window absorption. At the resonator center, the beam passes through a pressure antinode to

maximize the photoacoustic signal. To further increase the signal-to-noise ratio, this patented design is adapted for an optical multi-pass (of around 10 passes for a QCL) in the resonator height, or can enable the use of multiple sources thanks to the multiple laser beam entry points around acoustic nodes (fig.1a).

Experimental Setup

The setup depicted in fig. 2 and showed in fig. 3 was used to carry out first photoacoustic measurements as proof of concept. A laser diode emitting around 20 mW and set at 6490.02 cm^{-1} to target a rovibrational line of C_2H_2 is modulated at $f_0/2$. The laser diode temperature and current are controlled. The acoustic resonator is filled with C_2H_2 1000 ppmv in air. The signal is fed to a FPGA-based lock-in amplifier and demodulated at f_0 .

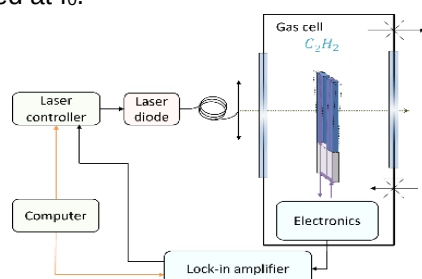


Fig. 2. Scheme of the experimental setup

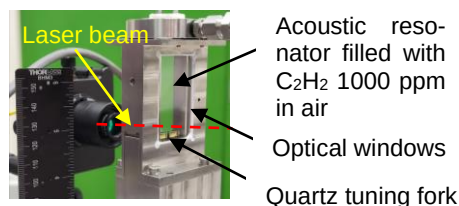


Fig. 3. Picture of the prototype

Results

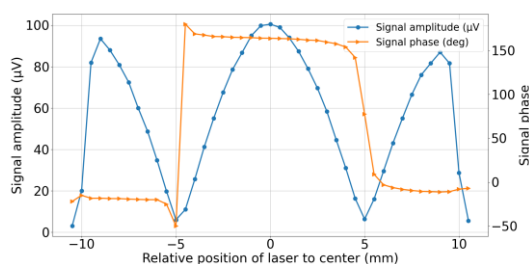


Fig. 4. Lateral scan of the acoustic mode by moving the laser beam in the resonator at f_0 .

In order to validate the sensor concept, the acoustic mode at frequency resonance was verified. The laser beam was manually moved along a horizontal line above the QTF prongs and the signal amplitude and phase were collected, resulting in fig. 3. The amplitude curve has two local minima which represent pressure nodes (green in fig.1c) and three local maxima which represent pressure antinodes (blue and red in fig. 1c). Moreover, there is an inversion in the phase between local maxima which represents

the opposite phase between prongs. A signal ratio of almost 17 was obtained between a node and an antinode, similar to simulation (ratio of 12). This result is promising for the decreasing of the background due to optical window absorption and validates the acoustic resonator concept.

The normalized noise equivalent absorption (NNEA) is the signal-to-noise ratio normalized by the generated signal and measurement bandwidth. To take into account all possible modulation schemes, the NNEA is defined as:

$$NNEA = \frac{H}{SNR \times \sqrt{\Delta f}} \quad (1)$$

where H is the heat amplitude generated in W.cm^{-1} due to gas excitation and relaxation. It takes in account the laser mean power, the overlap of the laser emission spectrum with gas absorption and the gas relaxation rate.

With a single pass and the laser beam centered in the resonator, a NNEA of $1.10^{-8} \text{ W.cm}^{-1}.\text{Hz}^{-1/2}$ was measured. It is important to note that the necessity of accommodating multiple optical sources with divergent beams while avoiding the acoustic window background results in a degraded NNEA. However, with the implementation of the optical multi-pass, the sensitivity will reach levels comparable to the state of the art.

Future work will concern the implementation of the optical multi-pass with QCL arrays in order to conduct measurements on CWAs simulants.

References

- [1] L. Fiorani, C. Ciceroni, I. Giardina, F. Pollastrone. Rapid non-contact detection of chemical warfare agents by laser photoacoustic spectroscopy. *Sensors* 24(1), 201 (2024); doi: 10.3390/s24010201
- [2] E. J. Pacsial-Ong, Z. P. Aguilar, Chemical warfare agent detection: a review of current trends and future perspective, *Front. Biosci. (Schol Ed)*, 5(2), 516–543, (2013); doi: 10.2741/S387
- [3] A.G. Bell. Upon the production of sound by radiant energy. (Gibbs brothers), 1881
- [4] N. Liberatore, G. Felizzato, S. Mengali, R. Viola, F. S. Romolo, A novel signal processing approach enabled by machine learning for the detection and identification of chemical warfare agent simulants using a GC-QEPAS system, *Forensic Sciences Research*, Volume 10, Issue 3, (2025); doi : 10.1093/fsr/owaf002
- [5] S. Xiong, X. Yin, Q. Wang, J. Xia, Z.Chen, H. Lei, X. Yan, A. Zhu, F. Qiu, B. Chen, Q. Wang, L. Zhang, K. Zhang, Photoacoustic Spectroscopy Gas Detection Technology Research Progress, *Applied Spectroscopy*, 78(2):139-158 (2024); doi: 10.1177/00037028231208712
- [6] R. Levy, M.Duquesnoy, J-M. Melkonian, L. Tran, M. Guais, G. Aoust, Detector employing a photoacoustic effect, FR24.05894 (2025)