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Photoacoustic gas spectroscopy with custom quartz tuning forks: on the path to industrialization

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Abstract: We present a 10-year retrospective overview of our work on photoacoustic spectroscopy, from the first analytical models to sensor industrialization, as well as our latest results. © 2024 The Author(s)

1. Motivation

The increasing need for gas detection solutions for climate change study, pollution or industrial processes monitoring brings new technological challenges.

To address these challenges, new technologies are of particular interest thanks to the new compromises they offer. In particular, there is an increasing need for high sensitivity multi-gas solutions. We believe that photoacoustic spectroscopy is a promising technology and that it would enable to fill in the gap between existing technologies.

Photoacoustic spectroscopy is an optical gas detection technique that consists in exciting the target gas with a modulated optical source, generating acoustic waves whose amplitude is proportional to the gas concentration, that are detected with a pressure-sensitive device such as a microphone. From the point of view of detection, this technique is highly linear and achromatic (as it is performed on the acoustic waves), while the laser wavelength can be independently chosen to target the gas of interest.

Nonetheless, this technique suffers from drawbacks such as sensitivity to environment, particularly to the gas matrix and to external sound and vibrations. We believe that the use of quartz tuning forks (QTF) as a detector (firstly demonstrated in 2002 by Kosterev et al. [1]) for photoacoustic spectroscopy will enable to tackle these issues. Indeed, QTFs act as quadrupole, that should render them immune to external sounds and they present high quality factors that should greatly reduce sensitivity to vibrations. However, detectors from the literature using QTFs suffer from other drawbacks, namely: a difficult optical alignment, particularly limiting when using mid-infrared or strongly divergent sources, and a sensitivity degraded compared to state-of-the-art detectors using microphones.

2. Overview of developments at ONERA from the lab...

Photoacoustic activities at ONERA started with the collaboration of two teams in 2013, merging their corresponding expertise on optical spectroscopy and quartz resonators.

Work began by establishing the analytical and finite element models (see Figure 1) used to describe the physical phenomena involved [2]. These unique models enabled to optimize and patent quartz resonators-based detectors for photoacoustic spectroscopy, while considering future industrial constraints, such as optical alignment. First prototypes were fabricated and tested on different gases: C_2H_2 , CO_2 , H_2O , NH_3 to confirm the detector versatility. We demonstrated state-of-the-art performances: we obtained the best quality factors at atmospheric pressure [3] as well as an optical alignment greatly facilitated while keeping state-of-the-art sensitivity [4].



Fig. 1. Finite element simulation of our optimized tuning fork (left), and realization (middle). Coupling of the QTF with a cylindrical acoustic resonator (right).

Moreover, we developed and patented an electronic detection method that should allow to limit sensor drifts and to reduce sensitivity towards environment [5].

3. ...towards industrialization & latest results

During our latest projects, we aimed for the industrialization of our technology. To this end, we designed in collaboration a first prototype integrating our detector, a quantum cascade laser array of 10 lasers emitting around $9\ \mu\text{m}$ for defense applications. We detected ammonia at $1049.5\ \text{cm}^{-1}$ using modulation amplitude of the pulsed QCL as shown in Figure 2. Thanks to our sensor specific design, facilitating optical alignment and allowing the use of strongly divergent optical sources such as QCLs, we demonstrated a sensitivity of $2.2\ 10^{-9}\ \text{cm}^{-1}\cdot\text{Hz}^{-1/2}$ close to the state-of-the-art.

We are currently optimizing our sensor design, integrating electronics in a single FPGA, and integrating the entire setup into a <3L, 3kg prototype. In parallel, we are studying the sensor dependence on environmental parameters such as temperature and pressure in order to evaluate the compliance of our sensor regarding gas detection standards. By considering industrial constraints from the very start of the development and thanks to our research demonstrating excellent sensor performances, we believe that an industrial transfer of our technology would be facilitated and would benefit to the gas detection industry.

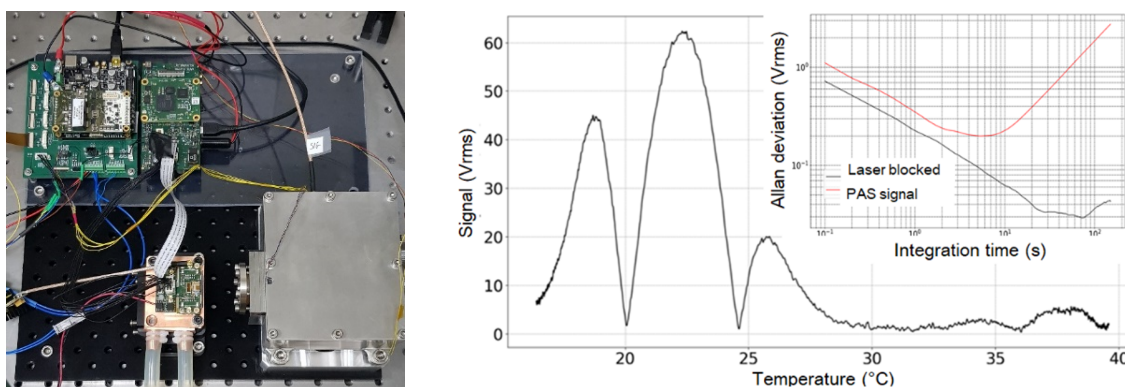


Fig. 2. Picture of our first integrated prototype (left) and measurement of NH_3 spectra and signal stability (right).

4. Acknowledgements

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5. References

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