Quartz-enhanced photoacoustic spectroscopy (QEPAS) sensor technology is based on a new approach to photoacoustic detection which employs a quartz tuning fork (TF) as a resonant acoustic transducer [1,2]. A QEPAS sensor detects the weak acoustic pressure wave that is generated when optical radiation interacts with a trace gas. The weak pressure wave excites a resonant vibration of a TF which is then converted into an electric signal by the piezoelectric effect. Subsequently, the electric signal, which is proportional to the concentration of the gas, is measured by a transimpedance amplifier. Merits of QEPAS compared to conventional resonant photoacoustic spectroscopy include QEPAS sensor immunity to environmental acoustic noise, a simple absorption detection module design, and its capability to analyze trace gas samples of $\sim 1$ mm$^3$ in volume.

This poster reports recent improvements of spectrophone design and QEPAS based sensor performance. In order to enhance the amplitude of the photoacoustic signal, it is advantageous to place a TF within a microresonator composed of two thin tubes, so that the microresonator yields a signal gain from 10 to 20. To-date, we have investigated the sensor performance with $l=4$ mm, 4.4 mm and 5 mm long metal tubes with ID=0.4 mm, 0.5 mm, 0.58 mm, 0.6 mm, 0.76 mm and 0.084 mm. A near-infrared fiber-coupled distributed feedback (DFB) diode laser (JDS Uniphase model CQF935/908-19600) was used as the QEPAS excitation source. The diode laser output was split into a 1:99 ratio by means of a fiber beam splitter (ThorLabs 10202A-99-APC). A small fraction of the laser light was sent to a commercial fiber-coupled reference gas module (Wavelength References, Mulino, OR) containing a sealed cell filled with a mixture of 5 Torr C$_2$H$_6$ and 145 Torr N$_2$, a fiber collimator, and a photodiode. The remaining laser power was directed to a spectrophone consisting of the TF and two tubes forming the acoustic microresonator. The spectrophone was placed into a vacuum-tight enclosure (the inner gas volume is $V \sim 1$ cm$^3$ when the spectrophone is installed) equipped with two sapphire windows and gas inlet and outlet. C$_2$H$_6$ in N$_2$ (10 ppmv) was used as a convenient target gas whose flow was set to 100 ccm. A control electronics unit was employed to measure the $f_T$ and $Q$-factor of the TF, to modulate the laser current at $f_L = 1/2 f_T$, to lock the laser wavelength to the targeted absorption line and to measure the current generated by the TF in response to the photoacoustic signal. For a specific length tube configuration, we varied the gas pressures by means of a pressure controller (MKS Type 649) to obtain signal amplitudes for different gas pressures.

The sensor performance was evaluated based on the SNR with a calibrated C$_2$H$_6$ gas mixture. In Ref. [3] it was shown that the TF noise is inversely proportional to the square root of the equivalent resistor $R$ of the TF. Therefore, the SNR is proportional to the product of signal amplitude and $\sqrt{R}$ of the TF. The optimal microresonator parameters are $l=4.4$ mm and ID=0.5 mm, with the two gaps between TF and the microresonator tubes set to between 30$\mu$m and 50$\mu$m.

Recent Advances of Quartz-Enhanced Photoacoustic Spectroscopy Sensor Technology

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Introduction

Quartz-enhanced photoacoustic spectroscopy (QEPAS) sensor technology is based on a new approach to photoacoustic detection which employs a quartz tuning fork (QTF) as a resonant acoustic transducer: A QEPAS sensor detects a weak acoustic pressure wave that is generated when optical radiation interacts with a trace gas. The pressure wave excites a resonant vibration of the QTF which is then converted into an electric signal by the piezoelectric effect. Subsequently, the electric signal, which is proportional to the concentration of the gas, is measured by a transimpedance amplifier. Hence, QEPAS compared to conventional resonant photoacoustic spectroscopy, a simple absorption detection module design, and its capability to analyze trace gas samples of as little as 1 ml is a major advantage.

In order to enhance the amplification of the photoacoustic signal, it is advantageous to place a QTF within an acoustic microresonator composed of two thin tubes, since a microresonator can yield signal gains from 10 to 20. In this work we investigated the QEPAS performance as a function of the microresonator geometrical parameters.

Quartz-Enhanced Photoacoustic Spectroscopy

Quartz Tuning Fork

In a QEPAS sensor, a quartz tuning fork (QTF) is utilized as a highly resonant sound transducer instead of a conventional sensitive broadband microphone.

QTF Characteristics
- Resonant frequency: ~32.3 kHz
- Force constant: ~2600 N/m
- Electrode length (c) ~ 3 x 10^7 m

Unique Properties of QTF
- Large dynamic range: linear from thermal noise to breakdown deformation
- Miniaturized size: 1 x 10^-6 m

Prototype of 4 Channel QEPAS Sensor

QEPAS Features
- Very small, planar, photonic device
- Rugged transducer - quartz monocrystal
- Low dimensional sample volume: ~2.0 ml
- High immunity to environmental acoustic noise
- Immunity to mechanical vibrations

Optimization of Microresonator Parameters

Configuration of Two-tube Microresonator

Due to the coupling gas flow from the two microresonator tubes, the pressure is high at the center of the QTF. The coupling of microresonator and QTF is most efficient when the resonant characteristics coincide. Thus, the measured Q-factor of the QTF (rather than the system) is dominant in this case.

Acoustic Microresonator

One-dimensional Acoustic Microresonator

If the cross-sectional dimensions of a resonator are much smaller than the acoustic wavelength, the excited sound field develops a spatial variation along the length of the resonator, i.e., a one-dimensional acoustic mode is formed. A microresonator tube used in QEPAS is in the first approximation equivalent to a one-dimensional acoustic resonator; if interactions with the QTF and another half of the microresonator are neglected.

Resonance Frequency of an Open Tube

Pressure distribution in the lowest acoustic mode of an open-end tube. Pressure nodes are located at the two ends.

Conclusions

- A microresonator composed of two thin tubes can be applied to enhance the amplification of a QEPAS signal.

Experiment and Results

Experimental Setup

SNR for Tubes of Different Length

- A calibrated CO2, NH3 and N2 gas mixture was used.
- The sound velocity, v, in CH4 is higher than in N2.

- QTF and microresonator: Q > 7000.

- The energy transfer between QTF and microresonator is most efficient when the resonant frequencies coincide. Thus, the measured Q-factor of the QTF (rather than the system) is dominant in this case.

- A calibrated CH4, gas mixture was used.
- QTF and microresonator: Q > 7000.

- The optimum tube radius is a compromise of the QTF Q, the rigidity, transmissivity and the QEPAS signal amplitude. The tube radius needs to be found experimentally.