Recent advances of quartz-enhanced photoacoustic spectroscopy sensor technology

F.K. Tittel*, L. Dong, A. A. Kosterev and D. Thomazy
Electrical and Computer Engineering Department, Rice University, 6100 S. Main St., Houston, TX 77005, USA
e-mail fkt@rice.edu

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 ~1 mm^3 in volume.

This poster reports recent improvements of spectraphone 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 microcresonator 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=4mm, 4.4mm and 5mm 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_2H_2 and 145 Torr N2, 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 ~1 cm^3 when the spectrophone is installed) equipped with two sapphire windows and gas inlet and outlet. C_2H_2 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_{TF} and Q-factor of the TF, to modulate the laser current at $f_L = 1/2\, f_{TF}$, 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_2H_2 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=4.4mm and ID=0.5mm, with the two gaps between TF and the microresonator tubes set to between 30μm and 50μm.

[1] A.A. Kosterev, F.K. Tittel, D. Serebryakov, A. Malinovsky and I. Morozov, "Applications of Quartz Tuning Forks in Spectroscopic Gas Sensing", Review of Scientific Instruments **76,** 043105 (2005)
[2] F. K. Tittel, Y.A. Bakhirkin, R.F. Curl, L. Dong, A.A Kosterev, R. Lewicki, S. So, D. Thomazy and G. Wysocki, "Recent progress of semiconductor laser-based infrared spectroscopic techniques", IQCLSW 2008 Conference, September 14-19, 2008, Ascona, Switzerland
[3] A.A Kosterev, Y.A. Bakhirkin, F.K. Tittel, S. McWhorther, B. Ashcraft, "QEPAS methane sensor performance for humidified gases", Applied Physics **B92,** 103 (2008)

Recent Advances of Quartz-Enhanced Photoacoustic Spectroscopy Sensor Technology

Frank K. Tittel, Lei Dong, Anatoliy A. Kosterev and David Thomazy*
Electrical and Computer Engineering Department, Rice University,
6100 S. Main St., Houston, Texas 77005, USA, fkt@rice.edu

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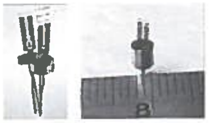
Introduction

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. 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 ~1 mm³ in volume.

In order to enhance the amplitude 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 sharply resonant sound transducer instead of a conventional sensitive broadband microphone.

QTF Characteristics

◆Resonant frequency ~32.8 kHz
◆Force constant ~26800 N/m
◆Electromechanical coefficient ~7×10^{-6} C/m

Unique Properties of QTF

◆Large dynamic range – linear from thermal noise to breakdown deformation
300K noise: $x\sim10^{-11}$ cm
Breakdown: $x\sim10^{-2}$ cm

◆Wide temperature range:
From 1.56K (superfluid helium) to ~700K

◆Extremely low internal losses:
Q~10 000 at 1 atm
Q~100 000 in vacuum

◆Acoustic quadrupole geometry
Low sensitivity to external sound

◆ Low cost (<$0.30)

QEPAS Features

◆Very small spectrophone size
◆Rugged transducer – quartz monocrystal
◆Ultrasmall sample volume - <1mm³
◆High immunity to environmental acoustic noise
◆Sensitivity is limited by the fundamental thermal TF noise - k_BT energy in the QTF symmetric mode, which can be directly observed
◆White noise spectrum - SNR scales as √t at least up to t=3 hours

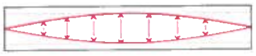
Prototype of 4 Channel QEPAS Sensor

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.

Stainless steel tubes used as QEPAS microresonator (ID<1 mm)



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

Resonance Frequency of an Open Tube

$$f = \frac{nc}{2(L+\Delta L)} \quad n=1,2,3,\ldots$$

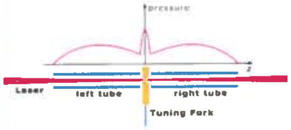
Usually, the fundamental resonance ($n=1$) of a tube is used for photoacoustic detection. The quantity $\Delta L\approx0.6r$ is the end correction, which can be understood as the effect of a mismatch between the one-dimensional acoustic field inside the tube and the three dimensional field outside that is radiated by the open end.

Inner Radius of Tube

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

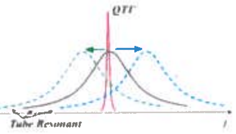
Optimization of Microresonator Parameters

Configuration of Two-tube Microresonator



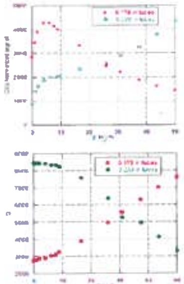
Due to the colliding gas flows from the two microresonator tubes, the pressure is high at the center of the QTF.

Coupling of Microresonator and QTF



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

Evidence of high efficient coupling



◆A calibrated CO_2, CH_4 and N_2 gas mixture was used.

◆The sound velocity, c, in CH_4 is higher than in N_2

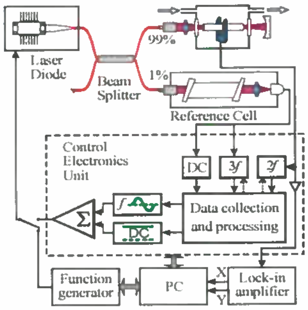
◆$f_1\approx c/2L$; for L=0.176", f_1=f_{TF} →[CH4]↑ →c↑ → f_1↑ →f_1>f_{TF} →Q↑ →signal↓

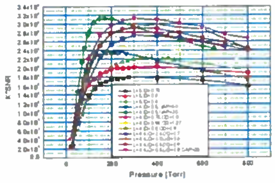
◆For L=0.2", f_1<f_{TF}→ [CH4]↑ →c↑ →f_1↑ → f_1≈f_{TF} →Q↓ →signal↑

◆There exists an optimum L that needs to be found out experimentally.

Experiment and Results

Experimental Setup





QEPAS SNR and Q for 4.4mm long and different inner diameter tubes

◆A calibrated C_2H_2 gas mixture was used

◆ID=0.4 mm yields the highest signal but not SNR

◆ID=0.6 mm: SNR high but low Q of the system, higher sensitivity to noise

◆ID=0.5 mm was selected as a compromise

SNR for Tubes of Different Length

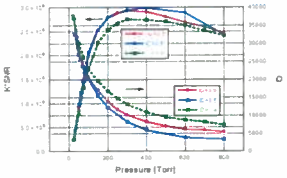
◆A calibrated C_2H_2 gas mixture was used

◆SNR ∝ √equivalent resistor × Signal Amplitude

◆K is a constant

◆Gaps between microresonator tubes and the QTF are 50μm except for where stated differently

◆L=4.4mm yields the highest SNR values



Conclusions

◆A microcresonator composed of two thin tubes can be applied to enhance the amplitude of a QEPAS signal.

◆Two 4.4mm-long tubes yield the highest SNR. Deviation from the half wavelength of a sound wave, 5.18 mm, is primarily due to interactions between the two tubes and with the QTF.

◆ Although a 0.6 mm ID tube has a higher SNR at >300 Torr pressure, the corresponding Q of the system is lowest. To ensure sufficient immunity to environmental acoustic noise, a 0.5 mm ID was selected as the optimum inner diameter for practical design.

◆Distance between the resonator tube end and the QTF surface also affects the SNR, smaller gap yielding higher SNR.

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