Trace Gas Detection Based on Multi-quartz-enhanced Photoacoustic Spectroscopy

Yufei Ma[1,2,*], Ying He[1], Xin Yu[1], Rui Sun[2], Frank K. Tittel[3]
[1]*National Key Laboratory of Science and Technology on Tunable Laser, Harbin Institute of Technology, Harbin 150001, China*
[2]*Post-doctoral Mobile Station of Power Engineering and Engineering Thermophysics, Harbin Institute of Technology, Harbin 150001, China*
[3]*Department of Electrical and Computer Engineering, Rice University, 6100 Main Street, Houston, Texas 77005, USA*
E-mail address: mayufei926@163.com

Abstract: A dual quartz tuning fork (QTF) instead of a single QTF as used in QEPAS was adopted in multi-quartz-enhanced photoacoustic spectroscopy (M-QEPAS) to increase signal strength by the addition of the detected QEPAS signals.
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1. Introduction

Trace gas sensor technologies are widely used in many applications [1], such as in environmental monitoring, atmospheric chemistry, industrial process control life science, and medical diagnostics. Quartz-enhanced photoacoustic spectroscopy (QEPAS) was first reported as a sensitive gas sensing technique in 2002 [2]. This technique uses a low cost, commercially available millimeter sized piezoelectric QTF as an acoustic wave transducer, which is capable of high detection sensitivity and immunity to ambient acoustic noise. In QEPAS technology, the acoustic energy is accumulated in the sharply resonant QTF, and not in a larger photoacoustic cell as in conventional photoacoustic spectroscopy.

Up to now, all the QEPAS sensors have used a single QTF to detect an acoustic wave signal generated by laser absorption. In this paper, we reported the development of a gas sensing technique based on a detection scheme using multiple QTFs, which we termed multi-quartz-enhanced photoacoustic spectroscopy (M-QEPAS). In M-QEPAS technology, the acoustic wave signal is detected by multiple QTFs simultaneously and the electrical signals generated by QTFs are added in order to increase the effective signal amplitude. In this paper, the number of QTFs was selected to be two to demonstrate the M-QEPAS technology and water vapor (H_2O) was chosen as the target analyte.

2. M-QEPAS sensor architecture

Commercially available QTFs with a resonant frequency f_0 of ~32.76 kHz is usually used in QEPAS sensors. The diameter of the QTF enclosure is ~ 3 mm and the gap between two prongs is ~ 300 µm. The focused laser should pass through the gap without touching, otherwise the QTF noise level will increase. In this paper, two QTFs with f_0 of 32.76 kHz were used and mounted parallel pointing in opposite directions for a convenient spatial arrangement, as shown in Fig. 1. A 1.395 µm continuous wave, distributed feedback (CW-DFB) fiber-coupled diode laser was employed as the laser excitation source. When the 7168.4 cm^{-1} H_2O absorption line was targeted the output power was about 12.6 mW. The laser beam was focused between the QTFs prongs using a plano-convex CaF_2 lens.

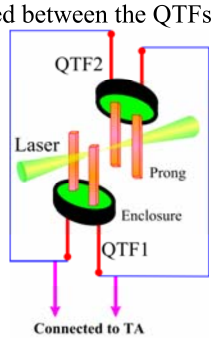

Fig. 1. Schematic of M-QEPAS with two QTFs. TA: transimpedance amplifier

3. QEPAS sensor performance and discussions

Air present in a laboratory environment was employed as the target analyte which contained 0.21% H_2O. The operating pressure was 1 atm. Initially, the distance between QTF1 and QTF2 was 150 µm in the M-QEPAS sensor system. The optimum modulation depth for M-QEPAS was found to be 0.49 cm^{-1}.

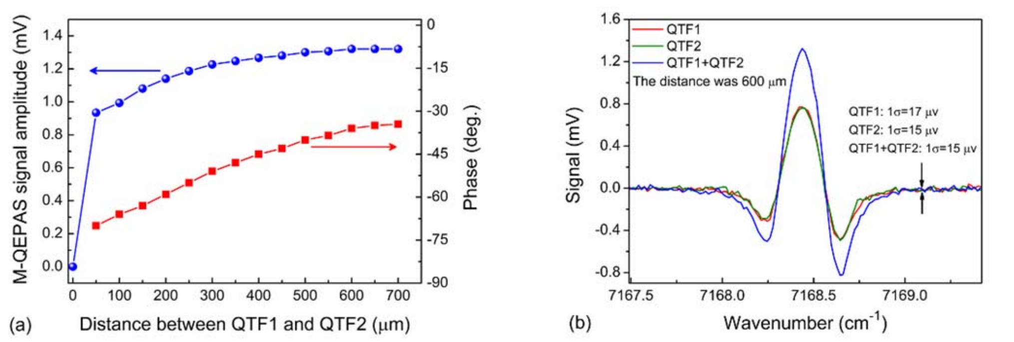

Fig. 2. (a) M-QEPAS signal amplitude and phase with a modulation depth of 0.49 cm^{-1} as a function of distance between QTF1 and QTF2. (b) Measured signal and noise with a modulation depth of 0.49 cm^{-1}

The M-QEPAS signal amplitude and phase as a function of distance between QTF1 and QTF2 are shown in Fig. 2(a). When the distance between QTF1 and QTF2 was zero, there was no signal. With increasing distance, the M-QEPAS signal amplitude and phase increased, but when the distance was > 600 μm, the M-QEPAS signal amplitude was no longer impacted by the distance between the two QTFs. This observed behavior is due to the coupling of the acoustic wave fields between QTF1 and QTF2. The measured 2*f* QEPAS signal and noise with a modulation depth of 0.49 cm^{-1} for QTF1, QTF2, and QTF1+QTF2 is shown in Fig. 2(b), respectively. The signal amplitude was 1.32 mV in M-QEPAS. Compared to signal levels of 0.77 mV, 0.76 mV for sensors employing QTF1 and QTF2, respectively, M-QEPAS resulted in a ~1.7 times signal enhancement. For optimal conditions, the signal enhancement of M-QEPAS (using two QTFs) should be two times compared to a single QTF. This inconsistency can be explained by the following fact. In order to obtain maximum signal strength, the modulation of the laser current should be at half of the QTF resonance frequency ($f = f_0/2$). In case of M-QEPAS technology, the acoustic wave signal will be detected by multiple QTFs simultaneously and the electric signal generated by QTFs will be added together. The measured resonance frequency f_0 of QTF1+QTF2 was 32757.3 Hz, and hence the modulation of the laser current was set to 32757.3/2 Hz. However, the frequency of 32757.3 Hz was not the same as that for QTF1 and QTF2 (it was 32756.9 Hz and 32757.9 Hz, respectively). Therefore, QTF1 and QTF2 in M-QEPAS did not provide the strongest response. Furthermore, there was a small difference in phase for QTF1 and QTF2. The smaller QTF difference in resonant frequency and phase will result in a greater signal improvement of M-QEPAS. If the difference in resonant frequency and phase between QTF1 and QTF2 is too large, the signal enhancement decreases and requires re-optimization of the QTFs.

The 1σ sensor noise level was 17 μV, 15 μV, and 15 μV for QTF1, QTF2, and QTF1+QTF2, respectively. A minimum detection limit (MDL) of 46.4 ppmv, 41.4 ppmv and 23.9 ppmv for QTF1, QTF2, and QTF1+QTF2, respectively, was obtained. The M-QEPAS approach resulted in a significantly improved MDL.

In conclusion, we demonstrated a trace gas detection scheme of M-QEPAS in which two QTFs were used as the acoustic transducer. Compared with a QEPAS sensor using a single QTF, M-QEPAS employing two QTFs obtained a signal enhancement of 1.7 times for the same operating conditions. A smaller difference in resonant frequency and phase of QTFs will result in greater signal improvement. Furthermore, the detection sensitivity of M-QEPAS can be further improved by using more than two QTFs.

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4. References

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