Water vapor concentration detection based on QEPAS sensor

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In this letter, a quartz-enhanced photoacoustic spectroscopy (QEPAS) based trace gas sensor using a quartz tuning fork (QTF) with resonant frequency of 40 kHz as the acoustic wave transducer was demonstrated for the first time. A 1.395 μm continuous wave (CW), fiber-coupled distributed feedback (DFB) diode laser was employed as the exciting source. Water vapor was selected as the target gas, and wavelength modulation spectroscopy (WMS) with 2nd harmonic detection was utilized. After optimization of the laser modulation depth, a minimum detection limit (MDL) of 139 ppmv was obtained.

1. Introduction

Optical trace gas sensors have attracted a wide range of interests in recent years because of merit of high sensitivity. Among these different type of optical sensors, direct laser absorption technique employing a multi-pass cell (MPC), where effective optical path length is extended to tens or even to hundreds of meters, typically allows to reach a detection limit of the analyte species at ppm or ppb levels [1-3]. However for ultra-high sensitive measurements these types of sensors are usually bulky due to the large size of a MPC and the increased number of optical components that are needed for laser beam alignment. Photoacoustic spectroscopy (PAS) is other one of widely used technologies which employ a broadband microphone for acoustic wave detection. It is based on photoacoustic effect, which means when the output of a laser is absorbed by a gas sample. The absorbed energy is transformed to heat energy by non-radiative processes, and will result in an increase of the local temperature and pressure in the sample. Therefore the absorption of the modulated laser in a gas sample leads to the generation of an acoustic wave. The intensity of the acoustic wave is related to the sample concentration which can be detected by a sensitive microphone. However, the microphone-based PAS cells have a low resonance frequency (usually < 2 kHz), which makes cells more sensitive to environmental and sample gas flow noise. And the size of the typical photoacoustic cell is large [4,5].

Quartz-enhanced photoacoustic spectroscopy (QEPAS) technique was first reported in 2002 [6], which is an improvement of traditional microphone-based PAS. This technique uses a low cost, commercially available mm sized piezoelectric quartz tuning fork (QTF) as an acoustic wave transducer with possesses a 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 large photoacoustic cell as in traditional PAS. QEPAS possesses a large dynamic range of nine orders of magnitude of the acoustic signal, a wide temperature range (of up to 700 K). Due to the merits of high sensitivity and compactness, QEPAS sensors have been widely used for trace gases detection [7-9].

QTF is the key element for QEPAS sensor performance because both signal level and noise level are related with it. For example the $1/f$ noise is frequency dependent and it decreases with increasing of resonant frequency. But up to now, QTF with resonant frequency of ~32.76 kHz is always used.

In this paper, a QEPAS sensor using a QTF with resonant frequency of 40 kHz is studied for the first time. Water vapor (H_2O) was selected as the target gas.

2. Experimental setup

The schematic of QEPAS sensor is shown in Fig. 1. The laser source was a diode laser emitting at 1.395 μm. It was a continuous wave (CW), fiber-coupled distributed feedback (DFB) laser. A QTF with resonant frequency of 40 kHz was used as the acoustic wave transducer. It had dimension of $\Phi 3 \times 8$ mm^3. The piezoelectric signal generated by the QTF was detected by a low-noise transimpedance amplifier (TA) with a 10 MΩ feedback

resistor and converted into a voltage. In order to improve the sensitivity, a wavelength modulation spectroscopy (WMS) with 2nd harmonic detection was utilized. The 2*f* signal was detected by a lock-in amplifier.
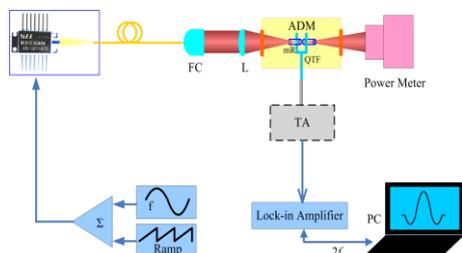

Fig. 1. Schematic of QEPAS sensor

3. Experimental results and discussions

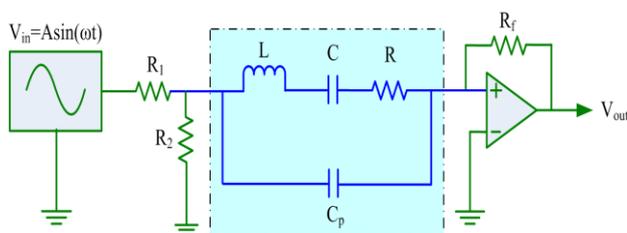Firstly the QTF parameters were measured. The measuring circuit is show in Fig. 2.

Fig. 2. Schematic of measuring circuit for QTF parameters

When QTF is represented by the equivalent serial resonant circuit, *R* is equivalent electrical parameters of resistance, *L* is equivalent electrical parameters of inductance, and *C* is the equivalent electrical parameters of capacitance. The measured results of *R* and *Q* factor at atmospheric pressure were 1942.4 kΩ and 3869 for 40 kHz QTF, respectively. The measured detection bandwidth was 10.3 Hz.
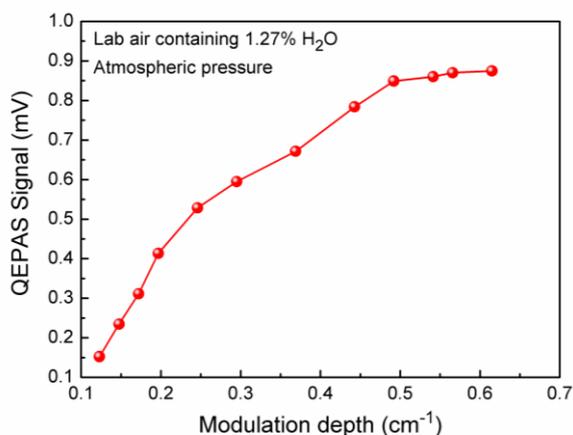

Fig. 3. Measured QEPAS signal amplitude as a function of laser modulation depth

In order to obtain the maximum 2*f* QEPAS signal, laser wavelength modulation depth must be optimized. For the purpose of determining the best operating conditions lab air was employed, which contained 1.27% H_2O as determined by means of a direct absorption method. The experimental result is shown in Fig. 3. The QEPAS signal amplitude increased with increasing of the modulation depth, but when the modulation depth was higher than 0.492 cm^{-1}, there was no significant change. Therefore, in the following experiments, a modulation depth of 0.492 cm^{-1} was adopted.

The measured 2*f* QEPAS signal and noise at modulation depth of 0.492 cm^{-1} using 40 kHz QTF is shown in Fig. 4. The noise was determined by the 2*f* signal far from the absorption line. The peak signal was 0.85 mV and the noise was 0.0093 mV. The signal to noise ratio (SNR) in this situation was 91. The minimum detection limit (MDL) can be calculated as 1.27%/91=139 ppmv.
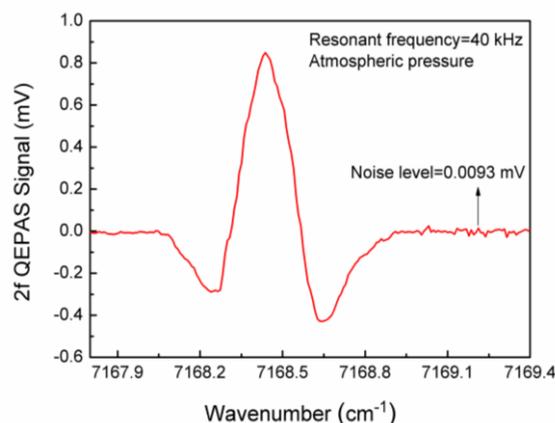

Fig. 4. 2f absorption signal and noise level for 40 kHz H_2O QEPAS sensor

4. Conclusions

In conclusion, a QEPAS based trace gas sensor using a QTF with resonant frequency of 40 kHz as the acoustic wave transducer was demonstrated for the first time. The measured parameters of *R* and *Q* factor at atmospheric pressure were 1942.4 kΩ and 3869, respectively. A 1.395 μm CW, DFB diode laser was employed as the exciting source. Water vapor was selected as the target gas, and wavelength modulation spectroscopy (WMS) with 2nd harmonic detection was utilized. A MDL of 139 ppmv was obtained. The MDL can be further improved when a micro-resonator architecture was used and a more stronger absorption line was selected.

References

[1] J. Vanderover, W. Wang, M. A. Oehlschlaeger, Appl. Phys. B **103**, 959 (2011).

[2] B. W. M. Moeskops, H. Naus, S. M. Cristescu, F. J. M. Harren, Appl. Phys. B **82**, 649 (2006).

[3] J. B. McManus, M. S. Zahniser, D. D. Nelson, Appl. Opt. **50**, A74 (2011).

[4] C. Grinde, A. Sanginario, P. A. Ohlckers, G. U. Jensen, M. M. Mielnik, J. Micromech. Microeng. **20**, 045010-1 (2010).

[5] A. Elia, F. Rizzi, C. Di Franco, P. M. Lugarà, G. Scamarcio, Spectroc. Acta A **64**, 426 (2006).

[6] A. A. Kosterev, Y. A. Bakhirkin, R. F. Curl, F. K. Tittel, Opt. Lett. **27**, 1902 (2002).

[7] Y. F. Ma, X. Yu, G. Yu, X. D. Li, J. B. Zhang, D. Y. Chen, R. Sun, F. K. Tittel, Appl. Phys. Lett. **107**, 021106 (2015).

[8] Y. F. Ma, R. Lewicki, M. Razeghi, F. K. Tittel, Opt. Express **21**, 1008 (2013).

[9] Y. F. Ma, Y. He, X. Yu, C. Chen, R. Sun, F. K. Tittel, Sensor Actuat. B-Chem. **233**, 388 (2016).

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