Integrated near-infrared QEPAS sensor based on a 28 kHz quartz tuning fork for online monitoring of CO$_2$ in the greenhouse

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A B S T R A C T

In this paper, a highly sensitive and integrated near-infrared CO$_2$ sensor was developed based on quartz-enhanced photoacoustic spectroscopy (QEPAS). Unlike traditional QEPAS, a novel pilot line manufactured quartz tuning fork (QTF) with a resonance frequency $f_0$ of 28 kHz was employed as an acoustic wave transducer. A near-infrared DFB laser diode emitting at 2004 nm was employed as the excitation light source for CO$_2$ detection. An integrated near-infrared QEPAS module was designed and manufactured. The QTF, acoustic micro resonator (AmR), gas cell, and laser fiber are integrated, resulting in a super compact acoustic detection module (ADM). Compared to a traditional 32 kHz QTF, the QEPAS signal amplitude increased by $> 2$ times by the integrated QEPAS module based on a 28 kHz QTF. At atmospheric pressure, a 5.4 ppm detection limit at a CO$_2$ absorption line of 4991.25 cm$^{-1}$ was achieved with an integration time of 1 s. The long-term performance and stability of the CO$_2$ sensor system were investigated using Allan variance analysis. Finally, the minimum detection limit (MDL) was improved to 0.7 ppm when the integration time was 125 s. A portable CO$_2$ sensor system based on QEPAS was developed for 24 h continuous monitoring of CO$_2$ in the greenhouse located in Guangzhou city. The CO$_2$ concentration variations were clearly observed during day and night. Photosynthesis and respiration plants can be further researched by the portable CO$_2$ sensor system.

1. Introduction

Carbon dioxide (CO$_2$) gas is an important component of the ambient air and greenhouse gas in the atmosphere. The emission sources of CO$_2$ include industrial waste gas, photosynthesis of plants, and automobile exhaust [1–4]. Highly sensitive detection of CO$_2$ concentration is of great significance in public health care, agricultural greenhouse monitoring, chemical plants hazardous detection, air pollutant monitoring, industrial process control, medical diagnosis, etc [5]. In the field of public health care, the detection of CO$_2$ can effectively evaluate the air quality level in public places [6]. Real-time monitoring of CO$_2$ concentration in agricultural greenhouses can improve the photosynthesis of fruits and vegetables by increasing the CO$_2$ content in time [7]. Monitoring the concentration of CO$_2$ in the atmosphere is an important way to analyze the greenhouse effect and haze phenomenon [8]. Therefore, it is necessary to develop highly sensitive CO$_2$ gas sensors.

In recent years, several CO$_2$ detection technologies have been extensively developed. The electrochemical sensor uses CO$_2$ gas to generate an oxidation-reduction reaction at the electrode of the electrolyte to obtain the CO$_2$ concentrations by measuring current [9]. These electrochemical CO$_2$ sensors have poor gas selectivity and short service life [10]. The solid electrolyte CO$_2$ sensor has attracted the attention of researchers because of its good sensitivity and the characteristics of being less affected by temperature [11–13]. The CO$_2$ sensors mentioned above have the shortcomings of relatively poor detection sensitivity, susceptibility to environmental noise, and slow response time, compared with the laser sensing technologies. Laser absorption spectroscopy (LAS) has the advantages of fast response, online monitoring, non-invasive, highly sensitive and selective detection, etc [14,15]. Tunable diode laser absorption spectroscopy (TDLAS) and photoacoustic spectroscopy (PAS) have been used for CO$_2$ gas detection. These sensors usually reach the detection limit of ppm CO$_2$ concentration level [16,17].
Photoacoustic spectroscopy (PAS) technology converts the absorption of light energy into sound energy and performs measurement [18]. The intensity of sound waves can be obtained through a microphone to invert the gas concentration. However, most microphone-based PAS cells usually have a low resonance frequency (<5 kHz), which makes such cells sensitive to environmental noises and sample gas flow noise.

An innovation of microphone-based PAS is quartz-enhanced photoacoustic spectroscopy (QEPAS) which was firstly reported in 2002 by Kosterev [19]. The novelty of this technology lies in the use of industrial mass-produced quartz tuning fork (QTF) as the acoustic wave transducer, replacing the miniature microphone in the traditional PAS, and realizing highly sensitive detection of weak photoacoustic signals [20–22]. QEPAS has become a research hotspot in recent years due to its immunity to environmental noise, high detection sensitivity, small size, wide dynamic range, and QTF operation insensitive to the excitation wavelength [23–35]. In recent years, researchers have used QEPAS technology to detect and analyze CO₂ gas concentration. In 2014, Pietro Patimisco et al. proposed a gas detection technology called intra-cavity QEPAS (I-QEPAS), which can obtain a detection limit of 300 ppt with an integration time of 20 s for CO₂ gas [36]. Zheng et al. developed a double pass QEPAS sensor for atmospheric CO₂ detection in 2015 [8]. A reflective concave mirror was used to enhance the absorption optical path to improve detection sensitivity, and consequently achieved a detection limit of 1.74 ppm with an integration time of 247 s. Recently, Maxime Duquesnoy et al. designed and fabricated a low-frequency QTF to adapt to gas molecules with slow relaxation rates and obtained a...
minimum detection limit of CO₂ gas of 44 ppm with an integration time of 1140 s [37]. Therefore, the gas sensor based on QEPAS is an excellent alternative for trace gases detection due to its merits of immunity to environmental noise, fast response, highly sensitive [38].

A typical PAS acoustic detection module (ADM) usually consists of a microphone and a gas cell. The acoustic resonators operating on longituudinal, azimuthal, and radial resonances are designed and manufactured in the internal structure of a gas cell, as shown in the Fig. 2 of ref [39]. However, in QEPAS acoustic detection module (ADM), the gas cell and acoustic micro resonator (AmR) are separated, as shown in Fig. 1(a). The separated AmR and gas cell results in a more complicated and unstable structure than traditional PAS ADM.

In this paper, we designed and demonstrated an integrated near-infrared QEPAS ADM based on a 28 kHz QTF. A pilot line manufactured custom 28 kHz QTF was employed as the photoacoustic transducer. The details of the 28 kHz QTF have been reported in the reference [35]. An integrated QEPAS ADM was designed and developed first. The laser fiber, QTF, resonator, gas cell, and preamplifier were integrated to form a compact and robust detection module, as shown in Fig. 1(b). A series of coaxial holes were drilled on the aluminum gas cell to integrate the fiber focuser, acoustic resonator, and buffer volume. The real pictures of the integrated ADM were shown in Fig. 1(c) and (d). The integrated ADM has an optimum on-beam AmR configuration in the inner architecture. No separated AmR was required to be assembled with the QTF. A compact QEPAS instrument based on the integrated ADM was developed for trace CO₂ gas detection. A near-infrared distributed feedback (DFB) laser diode emitting at 2.004 µm was employed as the excitation source. The instrument sensitivity, linear response and the feedback (DFB) laser diode emitting at 2.004

2. Experiment setup

The experimental setup of the CO₂ gas sensor system based on QEPAS is shown in Fig. 2(a). A near-infrared DFB laser diode (NIT Electronics) wavelength tuning range measured from 2.002 µm to 2.006 µm was employed as the excitation source. The output laser beam from the DFB laser was divided into two parts, 99% of which was used as the excitation light source for detection, and the remaining 1% was used for the reference cell which was filled with pure CO₂ sample. 99% of the laser was collimated and focused by an optical fiber focuser (OZ Optics). The focal length was ~11 mm, and the focused spot diameter was about 100 µm. The laser beam was focused through the AmR and QTF prong spacing in the photoacoustic detection module (ADM). Two cylindrical “holes” were drilled on both sides of the ADM wall perpendicular to the QTF prongs, thus resulting in acoustic resonance inside the “holes” as AmR. According to the one-dimensional pipe resonator theory, the optimum hole length L should be in the range of \( \lambda/4 < L < \lambda/2 \), where \( \lambda \) is the wavelength of the sound wave. Based on a 28 kHz QTF, the optimum length L should be 3.0 mm < L < 6.1 mm. According to our most recent work [40,41], for on-beam QEPAS configuration, the optimal length L and inner diameter (ID) were 5.4 mm and 0.6 mm respectively. The 3D model of the integrated QEPAS ADM by Solidworks software was shown in Fig. 2(b) and (c). Modulation and tuning of the laser current were controlled by applying a sinusoidal dither to the direct current ramp. The sinusoidal dither was set at the half of the QTF resonance frequency. The drive and temperature control of the laser were accomplished by the custom control electronic unit (CEU). 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 signal. The piezoelectric signals amplified by the preamplifier were transmitted to the lock-in amplifier (Stanford Research System, SR830 DSP) for second harmonic demodulation. The laser from the reference cell was detected by a photodiode and then introduced to CEU with the third harmonic setting. The 3f signal was used as an error signal of proportion integration differentiation (PID) module to lock the laser wavelength to the selected CO₂ absorption line. The demodulated signals were recorded and analyzed by a PC equipped with a data acquisition card (DAQ). The whole experiment was controlled by the automatic program written by LabView. The gas stream from two cylinders was fed to the mass flow controller (MFC) system to dilute 1000 ppm CO₂ in nitrogen (N₂). The diluted CO₂: N₂ mixture gas was controlled at the flow rate of 100 ml/min to flush the QEPAS ADM.

3. Experimental results

3.1. Frequency response of QTF

The frequency response of the bare QTF and the integrated QEPAS ADM is shown in Fig. 3. A function generator (Tektronix AFG3102) was used to provide a sinusoidal signal. The frequency of the sinusoidal signal was scanned from 27970 Hz to 28010 Hz with the step of 0.01 Hz. The peak-to-peak amplitude of the sinusoidal signal was set to 400 mV. The QTF output signal was demodulated by a lock-in amplifier (Stanford Research System, SR830 DSP) in 1 f mode. Fig. 3 shows that the resonance frequency and Q factor of bare QTF were 27987.4 Hz and 6802 respectively. This is due to the influence of air damping. The obtained resonance frequency and the Q factor of the integrated QEPAS ADM were 27986.5 Hz and 2809 respectively. The frequency slightly shift < 1 Hz, however the Q factor decrease by 3993. The huge decrease in Q factor can be attributed to the coupling energy transfer between the QTF and the integrated ADM. The decrease of Q factor indicates that more energy is stored in the AmR of the integrated ADM.

3.2. Influence of humidifier on the QEPAS

For gas molecules with slow relaxation rates such as CO₂, the amplitude and modulation frequency of the QEPAS signal largely depends on the vibration-translation (V-T) relaxation rate. Adding water vapor to the gas mixture can effectively promote the energy transfer of the excited CO₂ molecules in the V-T state [24]. A silicone hollow fiber membrane humidifier was added to the experimental gas circuit to humidify the CO₂ gas. The absolute humidity at room temperature was increased from ~2700 ppm to ~9200 ppm, which was determined by the performance of the hollow fiber membrane. According to the HITRAN database [42], the H₂O interference-free CO₂ absorption line located at 4991.25 cm⁻¹ with the intensity of 1.292 × 10⁻²¹ cm/molecule was selected as the target absorption line for detection. The temperature of the laser was controlled at 17.3 °C, the injection current was scanned from 120 mA to 140 mA, and the integration time of the
The lock-in amplifier was 1 s. The whole experiment was carried out under atmospheric pressure. Fig. 4 depicts the second harmonic QEPAS signal obtained by the CO$_2$ sensor system under dry and wet conditions respectively. The absolute humidity of the wet gas was limited by the performance of the used hollow fiber membrane. The QEPAS signal amplitude of the CO$_2$ sensor system was $9.31 \times 10^{-5}$ V under dry condition, and the QEPAS signal amplitude increased to $1.14 \times 10^{-4}$ V after humidification. As a result, the humidifier increases the QEPAS signal amplitude by 22.8% by promoting the relaxation rate of CO$_2$ molecules.

4. Sensor evaluation

The amplitude of the QEPAS signal $S$ is expressed by the following formula [43]:

$$S = K P_0 Q \alpha \varepsilon$$

(1)

where $K$ is the sensor constant, $P_0$ is the laser power, $Q$ is the quality factor of QTF, $\alpha$ is the peak intensity of the 2 $f$ absorption spectrum and $\varepsilon$ is the radiation-to-sound conversion efficiency, given by [44]:

$$\varepsilon = \frac{1}{\sqrt{1 + (2\pi f \tau)^2}}$$

(2)

where $f$ is the modulation frequency and $\tau$ is the relaxation time of the target gas. According to formulas (1) and (2), the amplitude of the QEPAS signal $S$ is inversely proportional to the frequency $f$. Therefore, a QTF with a low resonance frequency $f_0$ is conducive to obtaining large QEPAS signal. In this research, a QTF with a $f_0$ of 28 kHz was used. The advantages of low-frequency QTF were verified by comparing the QEPAS signal amplitude of a commercially available standard QTF with a frequency of 32.768 kHz and a custom pilot line manufactured QTF with a frequency of 28 kHz. Fig. 5 shows the results of measuring the QEPAS signal amplitude of 1000 ppm CO$_2$ with two QTFs with different frequencies under the same experimental conditions. It is found that the QEPAS signal amplitude was $3.81 \times 10^{-5}$ V when using a commercial QTF with a frequency of 32.768 kHz, and the QEPAS signal amplitude was $1.13 \times 10^{-4}$ V when a custom QTF with a $f_0$ of 28 kHz was used. It obvious that compared to a QTF with a $f_0$ of 32.768 kHz, the QEPAS signal amplitude increased by > 2 times when a QTF with a $f_0$ of 28 kHz was used. As a result, custom 28 kHz QTF is proved to show a better sensitivity for CO$_2$ detection than commercial 32.768 kHz QTF. The advantage of lower modulation frequency is obvious.

According to the gas absorption theory of photoacoustic spectroscopy, there is a good linear relationship between photoacoustic spectroscopy signal and concentration [45]. In order to verify the linear concentration response of the CO$_2$ sensor system based on integrated QEPAS module, QEPAS signals of different CO$_2$ concentrations were obtained. A 1000 ppm CO$_2$: N$_2$ mixture gas was diluted with 99.999% pure N$_2$ to obtained different CO$_2$ concentrations. At a standard atmospheric pressure, the gas stream was controlled at a flow rate of 100 ml/min. The CO$_2$ sensor system based on QEPAS ran in wavelength locking mode. The laser wavelength was locked the 4991.255 cm$^{-1}$ CO$_2$ absorption line by PID. Fig. 6 (a) shows the QEPAS signal amplitude of different concentrations of CO$_2$. Each concentration of CO$_2$ was measured by 60 data points. According to Fig. 6, QEPAS signal increased with the increment of CO$_2$ concentrations. The noise of the sensor system was measured by filling the gas cell with pure N$_2$. The obtained
The noise level was $4.55 \times 10^{-6}$ V with a 1σ standard deviation of $6.31 \times 10^{-7}$ V. This non-zero signal may come from the bottleneck at the QTF and the scattered light induced noise. Considering that the average QEPAS signal amplitude of 1000 ppm was $1.17 \times 10^{-4}$ V, the detection SNR was calculated to be $\sim 185.1$. Therefore, the detection limit of CO$_2$ is 5.4 ppm with an integration time of 1 s. The average value of QEPAS signal amplitudes at different concentration levels as a function of CO$_2$ concentration is shown in Fig. 6(b). The R-Square value obtained by linear fitting was 0.999, which proves that the CO$_2$ sensor system based on QEPAS has an excellent linear response to gas concentration.

To assess the long-term stability of the CO$_2$ sensor system based on the integrated QEPAS module, the amplitude of the 1000 ppm CO$_2$ signal was continuously measured in the wavelength locking mode, and the Allan variance analysis was performed. The 1000 ppm CO$_2$ standard gas was flushed into the gas cell with a flow rate of 100 ml/min and measured continuously for 30 min. Allan variance was performed on these data, and the results were shown in Fig. 7, which implies that a minimum detection limit (MDL) of 0.7 ppm was obtained with an optimum integration time of 125 s. Before 125 s, Johnson (thermal) noise was the dominant noise source, and after that, the system drifts started to dominate.

The basic elements of plant growth are CO$_2$ and H$_2$O, which photosynthesize carbohydrates and release oxygen [46]. Greenhouse system is regarded as an innovation of modern agriculture, which provides good environmental conditions for crops. Greenhouse is a relatively closed environment that the concentration of CO$_2$ in the greenhouse and the outside environment will have a certain difference. The CO$_2$ concentrations in the greenhouse will directly affect the growth of crops. The enrichment of CO$_2$ reduces the inhibition of photosynthesis by oxygen and increases the net photosynthesis of plants, which is the basis for the increase in the growth rate of crops caused by carbon dioxide under low and high light conditions [47]. At the same time, the increased carbon...
dioxide concentration will also increase the optimal temperature for growth [48]. CO2 enrichment approaches in the greenhouse usually include composting [49], chemical reaction [50] and greenhouse ventilation [51], etc. In addition, in the intelligent organic greenhouse, CO2 concentration should be accurately controlled to optimize the fertilization and photosynthesis. Traditional non-dispersive infrared analyzers became inefficient in many greenhouses, this is due to the cross-talking effect of H2O and CO2 absorption caused by high humidity.

A CO2 sensor system based on the integrated QEPAS module was used to continuously measure CO2 concentration in a semi-enclosed greenhouse located in Guangzhou city. The CO2 sensor was located 268 m away from S4 Huanan Express and 336 m away from Huangpu Avenue, which are two main streets of Guangzhou city, shown in Fig. 6 (a). For measurements, an inlet Teflon tube was placed next to crops and connected to a drying tube, shown in Fig. 8(b). The air in the greenhouse was pumped into the CO2 sensor system and fed to the integrated QEPAS module by a 6 m Teflon tube. Considering a maximum pump flow of 320 ml/min, the time delay for the sensor system was estimated to be ~14 s. A needle valve and a mass flow controller were used to control a 100 ml/min flow into the ADM to avoid possible gas flow noise. The CO2 sensor system with a dimension of 45 × 34 × 18 cm3, and a weight of ~10 kg, shown in Fig. 8(c). The results of continuous measurements of CO2 concentration for 24 h are shown in Fig. 8(d). The humidity in the greenhouse changed from 63.1%RH to 97.6%RH between day and night. The CO2 concentration dropped from 592 ppm to 269 ppm at 05:39–12:02. This is due to the vigorous photosynthesis of crops in the daytime. After 14:50, the CO2 starts to increase. Photosynthesis stops at night, crops respiration releases CO2, and the concentration of CO2 in the greenhouse gradually increases. According to our measurements, the CO2 in the greenhouse changed between 256 ppm and 608 ppm in 24 h.

5. Conclusions

An integrated near-infrared QEPAS sensor based on a 28 kHz QTF was demonstrated in this paper. A DFB laser diode with a center wavelength of 2,004 μm was employed as the excitation light source for CO2 detection. A pilot line manufactured QTF with a low resonance frequency f0 of 28 kHz was used as an acoustic wave transducer to improve the photoacoustic signal. Two cylindrical “holes” were drilled on both sides of the ADM wall perpendicularly to the QTF prongs, resulting in on-beam AmR QEPAS configuration. A super compact and integrated QEPAS module was developed consisting of QTF, acoustic micro resonator (AmR), gas cell, and laser fiber. The frequency of the integrated ADM was 27,986.5 Hz and the Q factor was 2809, which means that there was a good coupling resonance effect between the QTF and the ADM. A humidifier was added to the gas stream to promote the molecular relaxation rate of CO2 to increase the QEPAS signal amplitude. By comparing the QEPAS signal amplitude of 32 kHz QTF with that of 28 kHz QTF, it was obtained that the QEPAS signal amplitude of 28 kHz QTF was 160% higher than that of 32 kHz QTF. It is verified that 28 kHz QTF was more beneficial to improve the QEPAS signal. With the wavelength locking mode, the QEPAS signal amplitude of different concentrations of CO2 gas was continuously measured to calibrate the QEPAS sensor system. The functional relationship between the QEPAS signal amplitude and CO2 concentration was obtained, corresponding to a linear correlation coefficient of 0.999. A minimum detection limit (MDL) for CO2 is 5.4 ppm with an integration time of 1 s. With an integration time of 1 s, the MDL can be improved to be 0.7 ppm, indicating that the CO2 sensor system is capable of good stability. The developed integrated QEPAS sensor realized the continuous and accurate measurement of CO2 concentration in the greenhouse located in Guangzhou city. The high sensitivity of the integrated QEPAS sensor can meet the requirements for CO2 gas detection in applications such as atmospheric monitoring, industrial production, and medical diagnosis.

Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

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References

[1] K. Hashimoto, Global temperature and atmospheric carbon dioxide concentration, Glob. Carbon Dioxide Recycl. (2019) 5–17.
[2] M. Hoel, S. Kverndokk, Depletion of fossil fuels and the impacts of global warming, Renew. Energy Econ. 18 (2) (1996) 115–136.
[3] J. Hu, C. Zhong, C. Ding, Q. Chi, A. Walz, P. Monbaerts, M. Luo, Detection of near-atmospheric concentrations of CO2 by an olfactory subsystem in the mouse, Science 317 (5840) (2007) 953–957.
[4] J. Hansen, D. Johnson, A. Lasic, S. Lebedeff, P. Lee, D. Rind, G. Russell, Climate impact of increasing atmospheric carbon dioxide, Science 213 (4511) (1981) 957–966.
[5] A.A. Kosterev, L. Dong, D. Thomazy, F.K. Tittel, S. Overby, QEPAS for chemical analysis of multi-component gas mixtures, Appl. Phys. B 101 (3) (2010) 649–659.
[6] A.J. Feitz, G. Leamon, C. Jenkins, D.G. Jones, A. Moreira, L. Bressan, C. Melo, L. M. Dobeck, K. Repasky, L.H. Spangler, Looking for leakage or monitoring for public assurance? Energy Procedia 63 (2014) 3881–3890.
[7] D. Ko, G. Yoo, S.T. Yun, H. Chung, Impacts of CO2 leakage on plants and microorganisms: a review of results from CO2 release experiments and storage sites, Greenh. Gases 6 (3) (2016) 319–338.
[8] H. Zheng, L. Dong, X. Liu, Y. Liu, H. Wu, W. Ma, L. Zhang, W. Yin, S. Jia, Near-IR telecommunication diode laser based double-pass QEPAS sensor for atmospheric CO2 detection, Laser Phys. 25 (12) (2015), 125601.
[9] M. Struzik, I. Garbayo, R. Pfenninger, J.L.M. Rupp, A simple and fast electrochemical CO2 sensor based on Li2La2Zr2O7S x for environmental monitoring, Adv. Mater. 30 (44) (2018), 1804998.
[10] J.F. Currie, A. Essalik, J.C. Marusic, Micromachined thin film solid state electrochemical CO2, NO2 and SO2 gas sensors, Sens. Actuators B Chem. 59 (2–3) (1999) 225–241.
[11] Y. Shimizu, N. Yamashita, Solid electrolyte CO2 sensor using NASICON and perovskite-type oxide electrode, Sens. Actuators B Chem. 64 (1–3) (2000) 102–106.
[12] A. Yamamoto, T. Shinkai, A.G.M. Loy, M. Mohamed, F.H.B. Baldivinos, S. Yung, A. T. Quistain, T. Kida, Application of a solid electrolyte CO2 sensor to the performance evaluation of CO2 capture materials, Sens. Actuators B Chem. 315 (2020), 128105.
[13] N. Ma, S. Ide, K. Suematsu, K. Watanabe, K. Shimanoe, Novel solid electrolyte CO2 gas sensors based on c-axis-oriented V-doped La2O3–SrO–ZrO2 for environmental CO2 monitoring, ACS Appl. Mater. Interfaces 12 (19) (2020) 21515–21520.
[14] R. Cui, L. Dong, H. Wu, M. Liu, X. Xiao, J. Wu, C. Tittel, Three-dimensional printed miniature fiber-coupled multipass cells with dense spot patterns for ppb-level methane detection using a Near-IR diode laser, Anal. Chem. 92 (19) (2020) 13034–13041.
[15] R. Wada, J.K. Pearce, T. Nakayama, Y. Matsumi, T. Hiyama, G. Inoue, T. Shibata, Observation of carbon and oxygen isotopic compositions of CO2 at an urban site in Nagoya using Mid-IR laser absorption spectroscopy, Atmos. Environ. 45 (2011) 1168–1174.
[16] F. Xin, J. Li, J. Guo, D. Yang, W. Wang, Q. Tang, Z. Liu, Measurement of atmospheric CO2 column concentrations based on open-path TDLAS, Sensors 21 (5) (2021) 1722.
S. Qiao, Y. Gu, Y. Ma, Y. He, Y. Wang, Y. Hu, X. Yu, Z. Zhang, F.K. Tittel, A sensitive carbon dioxide sensor based on photoacoustic spectroscopy with a fixed wavelength quantum cascade laser, Sensors 19 (19) (2019) 4187.

L. Liu, H. Huan, W. Li, A. Mandalin, Y. Wang, L. Zhang, X. Zhang, Y. Yin, Y. Xu, X. Shao, Highly sensitive broadband differential infrared photoacoustic spectroscopy with wavelet denoising algorithm for trace gas detection, Photoacoustics 21 (2021), 100226.

A.A. Kosteret, V.A. Bakhrinik, R.F. Curl, F.K. Tittel, Quartz-enhanced photoacoustic spectroscopy, Opt. Lett. 27 (21) (2002) 1902–1904.

L. Dong, A.A. Kosteret, D. Thomary, F.K. Tittel, QEPAS spectroscopic design, optimization, and performance, Sensors 19 (19) (2019) 627–635.

K. Liu, X. Guo, H. Yi, W. Chen, W. Zhang, X. Gao, Off-beam quartz-enhanced photoacoustic spectroscopy, Opt. Lett. 34 (10) (2009) 1594–1596.

M. Duquesnoy, G. Aoust, J.M. Melkonian, R. Levy, M. Raybaut, A. Godard, QEPAS sensor using a radial resonator, Appl. Phys. B 127 (2021) 1–9.

A. Sampaolo, P. Patimisco, M. Giglio, A. Zifarelli, M. Giglio, A. Sampaolo, H. Wu, L. Dong, V. Spagnolo, Quartz-enhanced photoacoustic spectroscopy for multi-gas detection: a review, Appl. Phys. B 85 (2006) 301–306.

Z. Wang, Q. Wang, J.Y.L. Ching, J.C.Y. Wu, G. Zhang, W. Ren, A portable low-power QEPAS-based CO\textsubscript{2} isotope sensor using a fiber-coupled interband cascade laser, Sens. Actuators B Chem. 246 (2017) 710–715.

P. Breitegger, B. Schweighofer, H. Wegleiter, M. Knoll, B. Lang, A. Bergmann, Towards low-cost QEPAS sensors for nitrogen dioxide detection, Photoacoustics 18 (2020), 100169.

L. Hu, C. Zheng, M. Zhang, D. Yao, J. Zheng, Y. Zhang, Y. Wang, F.K. Tittel, Quartz-enhanced photoacoustic spectroscopic methane sensor system using a quartz tuning fork-embedded, double-pass and off-beam configuration, Photoacoustics 18 (2020), 100174.

M. Duquesnoy, G. Aoust, J.M. Melkonian, R. Levy, M. Raybaut, A. Godard, QEPAS sensors using a radial resonator, Appl. Phys. B 127 (2021) 1–9.

A. Sampaolo, P. Patimisco, M. Giglio, A. Zifarelli, A. F. Tittel, Radial-cavity quartz-enhanced photoacoustic spectroscopy, Opt. Lett. 46 (2021) 3917–3920.

D. Pinto, H. Moser, J.P. Wadlaw, S.D. Russo, P. Patimisco, V. Spagnolo, B. Lendl, Parts-per-billion detection of carbon monoxide: a comparison between quartz-enhanced photoacoustic and photothermal spectroscopy, Photoacoustics 22 (2021), 100244.

A. Sampaolo, C. Yu, T. Wei, A. Zifarelli, M. Giglio, P. Patimisco, H. Zuo, H. Zhu, L. He, H. Wu, L. Dong, G. Xu, V. Spagnolo, H\textsubscript{2}S quartz-enhanced photoacoustic spectroscopy sensor employing a liquid-nitrogen-cooled THz quantum cascade laser operating in pulsed mode, Photoacoustics 21 (2021), 100219.

S.D. Russo, A. Sampaolo, P. Patimisco, G. Mendoza, M. Giglio, C. Hoelzl, V.M. N. Passaro, H. Wu, L. Dong, V. Spagnolo, Quartz-enhanced photoacoustic spectroscopy exploiting low-frequency tuning forks as a tool to measure the vibrational relaxation rate in gas species, Photoacoustics 21 (2021), 100227.

L. Li, S. Qiao, Y. He, Y. Ma, Quartz tuning fork-based demodulation of an acoustic signal induced by photo-thermo-elastic energy conversion, Photoacoustics 22 (2021), 100272.

H. Zheng, Y. Liu, H. Lin, B. Liu, X. Gu, D. Li, B. Huang, Y. Wu, L. Dong, W. Zhu, J. Tang, H. Guan, H. Liu, Y. Zeng, F. Yang, Y. Luo, J. Zhang, J. Yu, Z. Chen, F. K. Tittel, Quartz-enhanced photoacoustic spectroscopy employing pilot line manufactured custom tuning forks, Photoacoustics 17 (2020), 100158.

P. Patimisco, S. Borri, I. Galiti, D. Mazzotti, G. Gusfredi, N. Akikusa, M. Yamashita, G. Scamarcio, P.D. Natale, V. Spagnolo, High finesse optical cavity coupled with a quartz-enhanced photoacoustic spectroscopic sensor, Analyst 140 (3) (2015) 736–743.

M. Duquesnoy, G. Aoust, J.M. Melkonian, R. Levy, M. Raybaut, A. Godard, Quartz-enhanced photoacoustic spectroscopy based on a custom quartz tuning fork, Sensors 19 (6) (2019) 1362.

H. Wu, L. Dong, H. Zheng, Y. Yu, W. Ma, L. Zhang, W. Yin, L. Xiao, S. Jia, F. K. Tittel, Beat frequency quartz-enhanced photoacoustic spectroscopy for fast and operation-free continuous trace-gas monitoring, Nat. Commun. 8 (2017) 15531.

A. Miklos, P. Hess, Z. Bozoki, Application of acoustic resonators in photoacoustic trace gas analysis and metrology, Rev. Sci. Instrum. 72 (4) (2001) 1937–1955.

H. Liu, H. Zheng, B.A.Z. Montanoa, H. Wu, R. Kim, M. Giglio, A. Sampaolo, P. Patimisco, W. Zhu, Y. Zhong, J. Yu, L. Dong, V. Spagnolo, On-beam quartz-enhanced photoacoustic spectroscopy based on a 28 kHz tuning fork, Photoacoustics 25 (2022), 100321.

H. Zheng, L. Dong, A. Sampaolo, H. Wu, P. Patimisco, X. Yin, W. Ma, L. Zhang, Single-tube on-beam quartz-enhanced photoacoustic spectroscopy, Opt. Lett. 41 (2016) 978–981.

https://hitran.iao.ru/

A.A. Kosteret, V.A. Bakhrinik, F.K. Tittel, S. Mewhorter, B. Ashcroft, QEPAS methane sensor performance for humidified gases, Appl. Phys. B 92 (1) (2008) 103–109.

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