Long-distance in-situ methane detection using near-infrared light-induced thermo-elastic spectroscopy

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ABSTRACT

A wavelength-locked light-induced thermo-elastic spectroscopy (WL-LITES) gas sensor system was proposed for long-distance in-situ methane (CH₄) detection using a fiber-coupled sensing probe. The wavelength-locked scheme was used to speed the sensor response without scanning the laser wavelength across the CH₄ absorption line. A small-size piezoelectric quartz tuning fork (QTF) with a wide spectral response range was adopted to enhance the photo-thermal signal. The optical excitation parameters of the QTF were optimized based on experiment and simulation for improving the signal-to-noise ratio of the LITES technique. An Allan deviation analysis was employed to evaluate the limit of detection of the proposed sensor system. With a 0.3 s lock-in integration time and a ~100 m optical fiber, the WL-LITES gas sensor system demonstrates a minimum detection limit (MDL) of ~11 ppmv in volume (ppmv) for CH₄ detection, and the MDL can be further reduced to ~1 ppmv with an averaging time of ~35 s. A real-time in-situ monitoring of CH₄ leakage reveals that the proposed sensor system can realize a fast response (<12 s) for field application.

1. Introduction

In-situ flammable, explosive or toxic gas detection is important to avoid major safety accidents in the places of coal mine, gas station, gas pipeline and chemical plant [1]. In order to achieve safety detection, these sensors are usually designed to have the ability of long-distance gas monitoring. Optical methods are well established in many applications because they facilitate analysis without contact between human beings and hazardous materials [2–5]. Among them, laser absorption spectroscopy for trace gas sensing are advantageous compared with other techniques, as they offer high gas specificity and sensitivity and permit real-time measurements [6–8]. Laser photo-thermal/photoacoustic spectroscopy, which has the merits of a zero-reference and a signal enhancement by increasing the laser excitation power, is an alternative to traditional laser absorption spectroscopy [9].

Quartz tuning fork (QTF), acting as a sharply resonant acoustic transducer, has been widely used in trace gas sensing since 2002 [10–17]. Compared to conventional resonant photoacoustic spectroscopy, the advantages of the technique named quartz-enhanced photoacoustic spectroscopy (QEPAS) include immunity to environmental acoustic noise, simple absorption detection module design, and the capability to analyze ultra-small volume gas samples (~1 mm³) [11]. However, gas sensors based on QEPAS technique require QTFs to be surrounded by the target gas, so it is difficult to achieve photo-electric separation, which limits the application of this technique in long-distance gas detection. Recently, the QTF was used as a thermal sensitive element in trace gas sensing and this technique was named as quartz-enhanced photothermal spectroscopy (QEPTS) or light-induced thermoelastic spectroscopy (LITES) [18–20]. Compared to the QEPAS technique, LITES is a non-contact measurement technique and can be used for long-distance gas sensing with an appropriate system deployment. Therefore, an in-situ long-distance gas sensing based on LITES was realized by using a fiber-coupled sensing probe.

On another aspect, the response time of a sensor system is usually important for an early warning of the accidents in in-situ flammable, explosive or toxic gas detection. In the traditional QTF-based sensor system, laser current was usually generated by a composite signal including a high-frequency sine-wave signal (modulation signal) and a sawtooth-wave or triangle-wave signal (scan signal) to obtain the
complete second harmonic signal waveform (2f-signal), and then the 2f-signal amplitude or peak-to-peak value was obtained to retrieve gas concentration [10–20]. In order to improve the detection performances, the frequency of the scan signal is usually low enough to adapt to the long lock-in integration time (usually hundreds of ms to 1 s) for improving the signal-to-noise ratio. Therefore, the response time of the sensor is always limited by the period of the scan signal (typically tens to hundreds of seconds). An alternative method is to lock the laser central wavelength at the selected absorption peak of the target gas by replacing the scan signal with a direct current (DC) bias signal. With this scheme, the scan time and the time for calculating the 2f-signal amplitude or peak-to-peak value are unneeded at the same time, so the response time of the sensor system can be reduced undoubtedly.

In this work, a miniature fiber-coupled sensing probe was employed innovatively in LITES for long-distance in-situ gas sensing. To realize a rapid response, a wavelength-locked detection scheme was adopted. A near-infrared distributed feedback diode laser was used as the excitation source to target the CH₄ absorption line at ~ 1653.72 nm. A commercial QTF with a resonant frequency of ~ 32 kHz was employed to measure the optical signal coupled back from the sensing probe ~ 100 m away. To improve the QTF signal and the detection sensitivity of the sensor system, the optical excitation parameters were optimized by experiment and simulation carefully. The performance of the developed LITES sensor system was investigated with experiment detailly. A real-time in-situ monitoring of gas leakage measurement was carried out to evaluate the response time of the proposed sensor system. The high detection sensitivity, fast response time and low-cost design make the proposed sensor system suitable for in-situ gas sensing.

2. Numerical simulation and optimization

To improve the detection sensitivity of the LITES-based gas sensor, the optical excitation parameters are very important and should be optimized carefully. In this part, we will provide a numerical model based on COMSOL Multiphysics software with finite element method to optimize the optical excitation parameters in LITES. As a comparison, detail experimental investigations were carried out to verify the simulation model.

2.1. Numerical model

The numerical model for the optimization of the optical excitation parameters is shown in Fig. 1. Two modules, solid mechanics and heat transfer in solid, are used for investigating mechanical deformation and thermal distribution of the QTF, respectively. The laser source is loaded on the surface of the QTF by the way of point heat source in heat transfer in the solid module. The power disturbance of the point heat source is related to the laser power disturbance and the absorption rate of the QTF surface. The silver film on the surface of the QTF is unconsidered in this model. The dependence of the LITES signal on the electrode pattern is discussed through a detailed comparison between simulation and experiment in Section 2.3. The heat power disturbance was set to 5 μW for qualitatively investigating the optimal optical excitation parameters. The geometric parameters of the QTF were built according to a commercial ~ 32 kHz QTF. The thickness t, length l and width w of the prong and the prong gap g were ~ 0.22, 3.32, 0.47 and 0.24 mm, respectively. A chamfering was also realized to better match the actual structure and the distance d_c from vertex was ~ 0.25 mm. There are two domains configured as quartz material in the numerical model and all of them are active in solid mechanics and heat transfer in solid models. Domain 1 was set as fixed constraint and Domain 2 was set as free to simulate the real situation for the QTF in LITES sensing application.

2.2. Frequency response of the QTF

To investigate the frequency response of the QTF at atmospheric pressure and environment temperature, a structural loss parameter of 9 × 10⁻⁶ and a viscous damping related to the velocity and acceleration of the QTF prongs were used for the finite element model [21]. As shown in Fig. 1 and Fig. 2a, a point heat source was loaded on the QTF surface at the bottom of the QTF prongs in this part. The displacement of the QTF prongs at point A (shown in Fig. 1) was used to evaluate the QTF signal since the QTF current is positively correlated with the prongs’ deformation [18]. Through eigenfrequency research, the resonant frequency of the QTF with an anti-symmetric mode is ~ 33,010 Hz. The simulated three-dimensional displacement field and the three-dimensional temperature field of the QTF with an anti-symmetric mode was given in Fig. 2a and b, respectively. Therefore, the frequency response of the QTF range from 33,000 Hz to 33,020 Hz was investigated by frequency domain analysis and the normalized simulation results were given in Fig. 3a. As a comparison, the frequency response of a commercial QTF used in WL-LITES sensor system was investigated by an electric excitation method [22]. The frequency response of the QTF was experimentally characterized by sweeping the frequency of the sine-wave excitation signal with an amplitude of ~ 0.25 mV generated by a function generator (Good Will Instrument, Model AFG-2225) and by measuring the QTF signal using a transimpedance amplifier with a 10 MΩ feedback resistor and a commercial lock-in amplifier (Stanford Research System, Model SR830). The experimental results are shown in Fig. 3b.

The resonant frequency and the Q-factor of the QTF are two important parameters for a QTF-based sensor system [23]. The Q-factor
of the QTF was calculated by measuring the bandwidth $\Delta f$ over which the amplitude is $1/\sqrt{2}$ of the resonant amplitude [24]. As shown in Fig. 3a, the resonant frequency $f_0$ of the QTF was simulated numerically to be $\sim 33009.77$ Hz. The bandwidth is $\Delta f = 33011.37$ Hz $-$ $33008.06$ Hz $= 3.31$ Hz. Therefore, the $Q$-factor is $f_0/\Delta f = 33009.77/3.31 \approx 9973$, which is a typical value for a commercial QTF at normal atmospheric pressure. The measured experimentally results reveal that the resonant frequency and the $Q$-factor are $32757.25$ Hz and $11374$, respectively, which are very close to the simulation results.

2.3. Excitation position optimization

With a heat source disturbance frequency of $33009.77$ Hz, the QTF response at different excitation position was investigated numerically. As shown in Fig. 4a, four different paths were investigated by adjusting the position of the point heat source in the finite element model in Multiphysics software and the simulated results are given in Fig. 4b. As a comparison, the QTF signals at five different paths (shown in Fig. 4c) on the QTF surface were investigated experimentally. The experimental schematic is shown in the Fig. 4e. A function generator with a DC offset of $3$ V and a $\sim 32.757$ kHz (resonant frequency of the employed QTF)
sine signal (200 mV peak-to-peak value) was used to modulate the laser driver. The current tuning coefficient of the laser driver is 20 mA/V and the power tuning coefficient of the laser is ~15 mW/A. Therefore, the sinewave signal with a peak-to-peak amplitude of 200 mV will lead to a light power disturbance of ~ 60 μW. After a path of ~ 100 m in fiber, the QTF signal at various hitting points on the QTF surface was investigated. The calculated light power disturbance at the output of the fiber-coupled focuser is ~ 18 μW due to a ~ 5 dB coupling loss during transmission. The measured laser beam diameter is ~ 200 μm with a propagation length of 15 mm (refer to Section 3.3). The current generated by the QTF was converted into a voltage signal by a transimpedance amplifier with a feedback resistor of 10 MΩ. The 1/f-signal was demodulated by a lock-in amplifier and the measurement results for different hitting points on the QTF surface were shown in the Fig. 4d.

Path A was proved to be the least sensitive area for LITES sensing application by the simulation results in Fig. 4b. For a commercial QTF, this area is usually covered by a silver film, which further deteriorates the sensitivity of this region since the reflectivity of the silver film is higher than that of the quartz material, which is not conducive to photothermal conversion. This is verified by the experimental results for path A and path E in Fig. 4d. For path E, the front surface without silver film at the bottom of the QTF improves the QTF signal. According to the simulation results, path B realizes a close sensitivity to that of path C. However, path B has a higher silver film coverage area for a commercial QTF and path C is more suitable for sensing application [18]. The effect of silver film was also verified by the experimental results for path B and C in Fig. 4d. The numerically simulated results for path A, B and C reveal that the most sensitivity area are located at the bottom of the QTF prongs. Therefore, we further investigated numerically path D at the bottom of the QTF prongs and the results reveal that the most sensitivity position was located at point B as shown in Fig. 4a, which is consistent with the experimental results in Fig. 4d and the previous research results [18–20,25]. The optimized excitation position (point B) was used for our in-situ WL-LITES sensing system.

2.4. Effect of the power characteristics

In addition to the excitation position, another factor affecting QTF signal is the power characteristics of the light source. A high power of the light source will linearly improve the light power disturbance in the LITES-based sensor system with a specific gas absorption strength, leading to a high heat power disturbance at the prong surface of the QTF. With a point heat source located at Point B, the numerically simulated QTF response as a function of heat source power disturbance range from 1 to 9 μW is shown in Fig. 5a. The results reveal that a high heat power disturbance is benefit to improving the QTF signal. Therefore, the QTF signal is proportional to the power of light source [20,25]. With a specific light power, the QTF signal may be also related to the power density of the light source. We investigated the influence of light power density by changing the power density of the heat source. As shown in Fig. 5b, the center of the heat source was set to be ~ 50 μm below the bottom of the two prongs in the front surface of the QTF. With a specific power disturbance of 5 μW, the simulated QTF response as a function of the heat source diameter is given in Fig. 5c. The results reveal that a high-power density with a specific power disturbance is more conducive to improve the QTF signal, but the effect is weak compared to the effect of the excitation position and power disturbance. For a commercial QTF, the area without silver film is limited at the bottom of the QTF, and a light source with a large diameter is also not conducive to thermo-elastic conversion.

2.5. Summary

To improve the detection sensitivity of the LITES-based sensor system, the optimal optical excitation parameters can be summarized as: (1) the optimal optical excitation position is located at the bottom of the QTF prongs at point B as can be seen in Fig. 4a; (2) an excitation source with a high power and a large power density is suggested.

3. Experimental setup for in-situ sensing application

3.1. Fabrication of the sensing probe

The sensing probe used in the WL-LITES sensor system was designed as a fiber-coupled structure realized by two FC/APC connectors with a 0.25 dB connection loss. The principle and photograph of the fiber-coupled probe is shown in Fig. 6. The incident light is collimated by a fiber-coupled collimator and reflected by a reflector to another fiber-
coupled collimator. The distance between the collimators and the reflector is ~15 cm. Therefore, a light path of ~30 cm was realized in the long-distance sensing probe whose coupling loss was measured to be ~5 dB at the wavelength of ~1653.72 nm.

3.2. Experimental setup

The schematic of the proposed WL-LITES sensor system is shown in Fig. 7a. A near-infrared distributed feedback (DFB) diode laser operating at ~1653.72 nm with a ~3.5 mW output optical power was used as the excitation source. The DFB laser was controlled by a commercial laser temperature controller (Thorlabs, Model TED 200C) and a laser current driver (Thorlabs, Model LDC202C). The laser temperature was controlled at 18 °C for all experiments in this research. The laser current driver was modulated by a composite signal generated by a home-made analog adder and a function generator (Good Will Instrument, Model AFG-2225). The output beam of the DFB laser was coupled to the sensing probe with a ~100 m single mode fiber (SMF) by a FC/APC connector. After an absorption path length of ~30 cm in the gas sample, the output light of the sensing probe ~100 m away was coupled to another SMF. Finally, the absorption light was focused by a fiber-coupled focuser (OZ optics Ltd., Model LPF-05) on the QTF surface for photo-thermal detection. As shown in Fig. 7b, the focus position is taken as the optimal excitation position according to the numerical simulation and experiment in the Section 2. The output optical power of the fiber-coupled focuser is ~1 mW without gas absorption due to a ~5 dB coupling loss of the probe. The piezoelectric current signal generated by the QTF was converted into a voltage signal by a trans-impedance amplifier (TA) with a 10 MΩ feedback resistor and demodulated by a commercial lock-in amplifier (Stanford Research System, Model SR830) to extract the second harmonic signal (2f-signal). The time constant of the lock-in amplifier and the slope filter were set to 0.3 s and 18 dB/octave, respectively, leading to a detection bandwidth of ~0.44 Hz. The 2f-signal was obtained by a digital acquisition card (DAQ) and used to retrieve the sample gas concentration.

3.3. Evaluation on beam characteristics

Considering the influence of beam characteristics on the LITES signal, the output laser beam characteristics of the fiber-coupled focuser was investigated experimentally by a commercial beam quality analyzer (Ophir-Spiricon, Model PY-III-HR-C-A). The laser beam passes through the SMFs and the sensing probe to the focuser with a path of ~100 m. The experimental results of the mode field distribution are shown in Fig. 8a. The corresponding intensity profiles and Gaussian fitting curve are shown in Fig. 8b. The measured beam profile shows a good Gaussian distribution, which may be due to the good single mode transmission characteristics of the employed SMF at ~1653.72 nm. The measured laser beam diameter is ~200 μm with a propagation length of 15 mm using the fiber-coupled focuser, which ensures that the beam is efficiently illuminated on the surface of the quartz material without being reflected by the silver layer.

3.4. Optimization of the modulation depth

The wavelength modulation depth is an important parameter in wavelength modulation spectroscopy (WMS) based sensor system. To realize an optimal detection sensitivity, the laser wavelength modulation depth was optimized at first. The optimization was carried out by scanning the laser wavelength around the CH4 absorption line at ~1653.72 nm. A 10 mHz scan signal (sawtooth wave) with an amplitude of 1 V and an offset of 3.2 V was generated by CH2 of the function generator to modulate the laser injected current. The dependence of the 2f-signal amplitude of the WL-LITES sensor as a function of the modulation voltage amplitude for a 10,000 ppmv CH4:N2 sample gas is shown in Fig. 9. The 2f-signal amplitude increases with the modulation voltage amplitude, but when the modulation voltage is higher than 0.15 V, no further significant change is observed. Therefore, a modulation voltage amplitude of 0.15 V can be found to be the optimum, leading to a modulation depth of ~0.21 cm⁻¹. The optimized modulation depth was used in the following experiments for performance improvement.

3.5. Determination on wavelength-locked parameters

As shown in Fig. 7a, a composite signal generated by an analog adder and a function generator was used to drive the DFB laser in the proposed WL-LITES sensor. Channel 1 (CH1) of the function generator was used to generate the high-frequency modulation signal with a frequency of f0/2 (f0 is the resonant frequency of the QTF), while channel 2 (CH2) was used to scan or lock the central wavelength of the laser to the absorption line of the target gas. A modulation voltage amplitude of 0.15 V was used, which is the optimized result in Section 3.4. Since wavelength-locked mode was employed in our LITES sensor system, the wavelength-locked parameters should be determined at first.

The gas sensing probe was put into a gas cell with a volume of ~700 mL, which was filled by a 10,000 ppmv CH4:N2 sample gas in this part. The laser temperature was controlled at 18 °C by a commercial laser temperature controller as mentioned before. The central emission wavelength of the laser was locked at the selected CH4 absorption peak in two steps.

First, a 10 mHz scan signal (sawtooth wave) with an amplitude of 1 V and an offset of 3.2 V was generated by CH2 of the function generator.

Fig. 7. (a) The schematic of the WL-LITES sensor system. DFB laser: distributed feedback diode laser; CD: laser current driver; TC: laser temperature controller; DAQ: data acquisition card; LIA: lock-in amplifier; QTF: quartz tuning fork; SMF: single mode fiber. (b) The light focus position employed in the proposed WL-LITES sensor system.
The current tuning coefficient of the laser driver is 20 mA/V, and a current scan range from 54 mA to 74 mA for a voltage scan signal with an amplitude of 1 V and an offset of 3.2 V generated by CH$_2$ of the function generator. The demodulated 2f-signal as a function of scan voltage and laser injected current for a 10,000 ppmv CH$_4$:N$_2$ sample gas is shown in Fig. 10a. With a laser operating temperature of 18 °C, the measured result reveals that the 2f-signal peak value can be obtained with a scan voltage of 3.2 V, leading to a laser injected current of 64 mA. As a comparison, the laser emission wavelength as a function of the injected current for different operating temperature range from 16 to 18 °C was investigated by a commercial Fourier transform spectrometer (Thermo Fisher Scientific, Model Nicolet iS50), and results are given in Fig. 10b. With a laser operating temperature of 18 °C, the emission wavelength of the laser is ~ 1653.72 nm for an injected current of 64 mA, which is consistent with the selected CH$_4$ absorption line in our LITES sensing system. Therefore, the laser wavelength locked parameters with an operating temperature of 18 °C and an injected current of 64 mA are determined for the selected CH$_4$ absorption line at ~ 1653.72 nm.

Second, a direct current (DC) bias voltage equal to the scan voltage corresponding to the 2f-signal peak value was set for CH$_2$ of the function generator to lock the central wavelength of the laser. The DC bias voltage was set to 3.2 V as claimed in the first step, leading to a laser injected current of 64 mA. The measured 2f-signal as a function of measurement time for a 10,000 ppmv CH$_4$:N$_2$ sample gas by locking the laser emission wavelength at ~ 1653.72 nm is shown in Fig. 11. The measured 2f-signal amplitude and the modulation depth as a function of modulation voltage amplitude for a 10,000 ppmv CH$_4$:N$_2$ sample gas at atmospheric pressure and environment temperature of ~ 25 °C are given in Fig. 9.
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measurement time was recorded and shown in Fig. 11. The average amplitude of the 2f-signal is 2.3 mV, which is consistent with the 2f-signal peak value obtained in a scan period as shown in Fig. 10a. The measured values vary around 2.3 mV without a baseline drift, which reveal that the laser emission wavelength was locked at the selected CH₄ absorption line steadily.

4. Results and discussion

4.1. Linearity of the proposed WL-LITES sensor system

The linearity of the proposed WL-LITES sensor system was evaluated by measuring CH₄ gas sample with a concentration range from 0 to 10,000 ppmv, where the balance gas was N₂. During experiment, the gas sensing probe was put into a gas cell with a volume of ~ 700 mL. CH₄ samples with different concentration levels diluted in N₂ were prepared using a commercial gas dilution system (Environics, Model S4000). By locking the laser wavelength to target the selected CH₄ absorption line at ~ 1653.72 nm, the 2f-signal amplitude for different CH₄ concentration levels shown in Fig. 12a were obtained and sent to a LabVIEW-based laptop. For each concentration, the 2f-signal amplitudes were recorded for ~ 600 s with a data sampling rate of 1 Hz. As shown in Fig. 12b, the averaged 2f-signal amplitude for each concentration level was used to evaluate the linearity of the sensor system. The high R-square value of 0.9998 reveals that the proposed WL-LITES sensor system realizes a high linear relation between the CH₄ concentration level and the 2f-signal amplitude.

4.2. Allan deviation

To evaluate the long-term stability and detection limit of the WL-LITES sensor system, the sensing probe was immersed in a gas cell filled with ultra-highly pure N₂ and the Allan deviation analysis was performed. The DFB laser central wavelength was locked at the selected absorption peak of CH₄. The measurement was carried out for ~ 30 min and the measured 2f-signal amplitude are shown in Fig. 13a. The Allan deviation results were converted to CH₄ concentration values according to the linear fitting curve provided in Section 4.1. As shown in Fig. 13b, the Allan deviation (in ppmv) decreases by increasing the averaging time, which is proportional to 1/√τ as shown by the red solid line in Fig. 13b. The results reveal that the dominant noise in the WL-LITES sensor system follows from thermal noise. For a 0.3 s integration time, a sensitivity of ~ 11 ppmv can be realized and a minimum detection limit of ~ 1 ppmv can be reached for a ~ 35 s averaging time.

5. Field experiment

A field CH₄ leakage experiment was carried out to evaluate the long-distance in-situ monitoring capability of the WL-LITES sensor on the Jilin University campus. As shown in Fig. 14a, the WL-LITES sensor system was located in room No.539 in Area D, Tangao Qing building except for the sensing probe. The sensing probe ~ 100 m away was placed outside the State Key Laboratory of Integrated Optoelectronics to monitor the variation of gas concentration levels during CH₄ leakage, which is marked as Test Point in Fig. 14a. The photograph shown in Fig. 14b and 14c were taken at the Test Point during the field experiment. The environmental temperature and the wind speed were ~ 20 °C and 1 m/s. A 10,000 ppmv CH₄:N₂ mixture was used for leakage detection and the distance between the leakage source and the sensing probe was ~ 10 cm as shown in Fig. 14c. The response time is an important parameter for the design of a sensor for the desired application. The rise time and fall time are defined as the time required for a sensor to reach 90 % of its full response/recovery ability with respect to the baseline when the gas is turned on or off. The measured CH₄ concentration curve as a function of measurement time is given in Fig. 14d, where the gas leakage starts at ~ 100 s and lasts about ~ 50 s. A rise time of ~ 11.8 s and a fall time of ~ 3.5 s can be realized. The rise time is obviously longer than the fall time and during the diffusion equilibrium period, the measured CH₄ concentration is ~ 5200 ppmv although a 10,000 ppmv CH₄:N₂ mixture was employed. This may be because a rapidly diffusion rate of the sample gas in the air. The rapid response (< 12 s) for gas leakage is helpful to detect leakage sources in time and to avoid safety accidents in the field application. This experiment proves the sensor’s ability of long-distance in-situ gas monitoring.

6. Conclusions

An in-situ CH₄ sensor system was proposed based on a novel wavelength-locked light-induced thermo-elastic spectroscopy (WL-LITES) and a fiber-coupled sensing probe. To enhance the QTF signal and improve the detection sensitivity, the optical excitation parameters were optimized by experiment and a proposed finite element model carefully. A commercial ~ 32 kHz quartz tuning fork (QTF) instead of a traditional photoelectric detector was used to establish a sensor system with small size, low cost and wide spectral response range. Wavelength modulation spectroscopy (WMS) combined with the second harmonic detection sensitivity, low cost design and rapid response, which is suitable for real-time in-situ gas sensing. In addition, although a ~ 100 m conductive fiber was employed in the sensor system, it is possible to realize a relatively longer distance in-situ gas detection by simply using a longer fiber due to the low transmission loss in the near infrared range of the SMF. Because of a wide spectral response range of the QTF in the optical-domain, the proposed WL-LITES sensor system can be used for the detection of any kind of gas species with interference-free absorption line located in the transmission window of the optical fiber.
Fig. 13. (a) Measured 2f-signal amplitude as a function of measurement time for ultra-highly pure N₂. (b) Allan deviation plot (in ppmv) of the WL-LITES sensor system with a 0.3 s integration time for ultra-highly pure N₂ at atmospheric pressure and an environmental temperature of ~ 25 °C.

Fig. 14. (a–c) Photograph of the long-distance gas leakage measurement on Jilin University campus, Changchun, PR China. (d) Measured CH₄ concentration curve as a function of measurement time.
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Declaration of Competing Interest

The authors declare that there are no conflicts of interest.

References

[1] K. Chen, M. Gao, S. Liu, B. Zhang, H. Deng, Y. Zheng, Y. Chen, C. Luo, L. Tao, M. Lou, Q. Yu, Fiber-optic photoacoustic sensor for remote monitoring of gas micro-leakage, Opt. Express 27 (2019) 4648–4659, https://doi.org/10.1364/OE.27.004648.
[2] C. Bauer, P. Greiser, J. Burgmeier, G. Holl, W. Schade, Pulsed laser surface fragmentation and mid-infrared laser spectroscopy for remote detection of explosives, Appl. Phys. B 85 (2006) 251–256, https://doi.org/10.1007/s00340-006-2372-1.
[3] G.M. Gibson, B. Sun, M.P. Edgar, D.B. Phillips, N. Hempler, G.T. Maker, G. P. Malcolm, M.J. Padgett, Real-time imaging of methane gas leaks using a single-pixel camera, Opt. Express 25 (2017) 2998–3005, https://doi.org/10.1364/OE.25.002998.
[4] B. Li, C. Zheng, H. Liu, Q. He, W. Ye, Y. Zhang, J. Fan, Y. Wang, Development and measurement of a near-infrared CH4 detection system using 1.654 μm wavelength-modulated diode laser and open reflective gas sensing probe, Sens. Actuators B Chem. 225 (2016) 188–196, https://doi.org/10.1016/j.snb.2015.11.037.
[5] C.S. Goldenstein, R. Mitchell Spearrin, R.K. Hanson, Fiber-coupled diode-laser sensors for calibration free stand-off measurements of gas temperature, pressure, and composition, Appl. Opt. 55 (2016) 479–484, https://doi.org/10.1364/AO.55.004790.
[6] L. Tombez, E.J. Zhang, J.S. Orcutt, S. Kamalpurkar, W.M.J. Green, Methane absorption spectroscopy on a silicon photonic chip, Optica 4 (2017) 1322–1325, https://doi.org/10.1364/OPTICA.4.001322.
[7] L. Dong, F.K. Tittel, C. Li, N.P. Sanchez, H. Wu, C. Zheng, Y. Yu, A. Sampalo, R. J. Griffin, Compact TDLAS based sensor design using interband cascade lasers for mid-IR trace gas sensing, Opt. Express 24 (2016) A528–535, https://doi.org/10.1364/OE.24.00A528.
[8] J.H. Northern, S. O’Hagan, B. Fletcher, B. Gran, P. Evart, C.S. Kim, M. Kim, C. D. Merritt, W.W. Bewley, C.L. Canedy, J. Abell, I. Vurgaftman, J.R. Meyer, Mid-infrared multi-mode absorption spectroscopy using interband cascade lasers for multi-species sensing, Opt. Lett. 40 (2015) 4186–4189, https://doi.org/10.1364/OL.40.004186.
[9] W. Jin, Y. Gao, F. Yang, H.L. Hu, Ultra-sensitive all-fibre photothermal spectroscopy with large dynamic range, Nat. Commun. 6 (2015) 1–8, https://doi.org/10.1038/ncomms7757.
[10] A.A. Kosterev, Yu. A. Balakrin, R.F. Curl, F.K. Tittel, Quartz-enhanced photoacoustic spectroscopy, Opt. Lett. 27 (2002) 1902–1904, https://doi.org/10.1364/OL.27.001902.
[11] A.A. Kosterev, F.K. Tittel, D.V. Serebryakov, A.L. Malinovsky, I.V. Morozov, Applications of quartz tuning forks in spectroscopic gas sensing, Rev. Sci. Instrum. 76 (2005) 043105, https://doi.org/10.1063/1.1884196.
[12] K. Liu, X. Guo, H. Yi, W. Chen, W. Zhang, X. Gao, Off-beam quartz-enhanced photoacoustic spectroscopy, Opt. Lett. 34 (2009) 1594–1596, https://doi.org/10.1364/OL.34.001594.
[13] H. Yi, W. Chen, S. Sun, K. Liu, T. Tan, X. Gao, T-shape microresonator-based high sensitivity quartz-enhanced photoacoustic spectroscopy sensor, Opt. Express 20 (2012) 9189–9196, https://doi.org/10.1364/OE.20.009187.
[14] P. Patimisco, G. Scamarcio, F.K. Tittel, V. Spagnolo, Quartz-enhanced photoacoustic spectroscopy: a review, Sensors 14 (2014) 6165–6206, https://doi.org/10.3390/s140506165.
[15] P. Patimisco, A. Sampalo, H. Zheng, L. Dong, F.K. Tittel, V. Spagnolo, Quartz-enhanced photoacoustic spectrophones exploiting custom tuning forks: a review, Adv. Phys. X 2 (2016) 169–187, https://doi.org/10.1080/23746149.2016.1271285.
[16] L. Hu, C. Zheng, J. Zheng, Y. Wang, F.K. Tittel, Quartz tuning fork embedded off-beam quartz-enhanced photoacoustic spectroscopy, Opt. Lett. 44 (2019) 2562–2565, https://doi.org/10.1364/OL.44.002562.
[17] P. Patimisco, A. Sampalo, L. Dong, F.K. Tittal, V. Spagnolo, Recent advances in quartz enhanced photoacoustic sensing, Appl. Phys. Rev. 5 (2018) 011106, https://doi.org/10.1063/1.5013612.
[18] Y. Ma, Y. He, Y. Tong, X. Yu, F.K. Tittel, Quartz-tuning-fork enhanced photothermal spectroscopy for ultra-high sensitive trace gas detection, Opt. Express 26 (2018) 32103–32110, https://doi.org/10.1364/OE.26.032103.
[19] Y. He, Y. Ma, Y. Tong, X. Yu, F.K. Tittel, Ultra-high sensitive light-induced thermoelastic spectroscopy sensor with a high Q-factor quartz tuning fork and a multipass cell, Opt. Lett. 44 (2019) 1904–1907, https://doi.org/10.1364/OL.44.001904.
[20] Y. Ma, Y. He, P. Patimisco, A. Sampalo, S. Qiao, X. Yu, F.K. Tittel, V. Spagnolo, Ultra-high sensitive trace gas detection based on light-induced thermoelastic spectroscopy and a custom quartz tuning fork, Appl. Phys. Lett. 116 (2020) 011103, https://doi.org/10.1063/1.5129014.
[21] Y. Cao, W. Jin, H.L. Ho, Optimization of spectrophotometer performance for quartz-enhanced photoacoustic spectroscopy, Sens. Actuators B Chem. 174 (2012) 24–30, https://doi.org/10.1016/j.snb.2012.08.014.
[22] A.A. Kosterev, P.R. Baerki, L. Dong, M. Reed, T. Day, F.K. Tittel, QEPAS detector for rapid spectral measurements, Appl. Phys. B 100 (2010) 173–180, https://doi.org/10.1007/s00340-010-3975-0.
[23] T. Wei, H. Wu, L. Dong, F.K. Tittel, Acoustic detection module design of a quartz-enhanced photoacoustic sensor, Sensors 19 (2019) 1093, https://doi.org/10.3390/s19051093.
[24] X. Chen, X. Feng, X. Liu, X. Zeng, Y. Xu, Low-cost quartz tuning fork based methane sensor for coal mine safety applications, Sens. Actuators B Chem. 295 (2019) 7–11, https://doi.org/10.1016/j.snb.2019.05.066.
[25] L. Hu, C. Zheng, Y. Zhang, J. Zheng, Y. Wang, F.K. Tittel, Compact all-fiber light-induced thermoelastic spectroscopy for gas sensing, Opt. Lett. 45 (2020) 1894–1897, https://doi.org/10.1364/OL.388754.

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