High-sensitivity miniature dual-resonance photoacoustic sensor based on silicon cantilever beam for trace gas sensing

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ABSTRACT

We report a miniature dual-resonance photoacoustic (PA) sensor, mainly consisting of a small resonant T-type PA cell and an integrated sensor probe based on a silicon cantilever beam. The resonance frequency of the miniature T-type PA cell is matched with the first-order natural frequency of the cantilever beam to achieve double resonance of the acoustic signal. The volume of the designed T-type PA cell is only about 2.26 cubic centimeters. A PA spectroscopy (PAS) system, employing the dual-resonance photoacoustic (PA) sensor as the prober and a high-speed spectrometer as the demodulator, has been implemented for high-sensitivity methane sensing. The sensitivity and the minimum detection limit can reach up to 2.0 pm/ppm and 35.6 parts-per-billion, respectively, with an averaging time of 100 s. The promising performance demonstrated a great potential of employing the reported sensor for high-sensitivity gas sensing in sub cubic centimeter-level spaces.

1. Introduction

Trace gas detection has a significant application in many areas, e.g., the safety supervision in underground, the environmental air monitoring, and the studies of diseases prevention and insect respiration [1–5]. Laser-based photoacoustic (PA) spectroscopy (PAS) has been widely used for trace gas measurement, owing its superior characteristics of high sensitivity, miniaturization capability, strong gas selectivity and fast response [6–17]. The PA phenomenon is originated from the periodical light absorbing of gas molecules, leading to periodical release of heat. As a result, the gas space expands and then generates acoustic waves, the pressure of which is approximately linearly related to the concentration of the measured gases [18–21]. The gas concentration is obtained from the magnitude of the acoustic signal, which may be detected by a microphone or a tuning fork in a PAS system. Therefore, the performance of an acoustic detector plays a significant role in the measurement sensitivity of a PAS system.

In recent years, the quartz tuning fork (QTF) featuring high Q-value and small size, has been widely used in PAS [22–28]. Quartz enhanced photoacoustic spectroscopy (QEPA) [3,10,12,29–35], quartz enhanced photothermal spectroscopy (QEPTS) [36–39] and light-induced thermoelastic spectroscopy (LITES) [40–42] are typical applications of QTF for high-sensitivity gas sensing. However, the metal conductive electrodes on the QTFs can be easily damaged when measuring corrosive gases, which limits the application of QTF in corrosive gas measurements. As an alternative PA signal detector, the fiber-optic acoustic sensor has also been widely applied in PAS system for the detection of various trace gases with advantages of good stability, wide working range and high sensitivity [43,44]. Cao et al. reported a novel miniature PA sensor based on a polymer diaphragm-based fiber-optic microphone, which realized the transmission of two light beams by a single optical fiber [6]. The minimum detection limit (MDL) for acetylene (C2H2) gas was 4.3 parts-per-million (ppm). In 2021, Li et al. reported a miniaturized single-fiber PA sensor using a cantilever beam as a fiber-optic microphone and an MDL of 8.4 ppm has been achieved by employing a simple and stable demodulator [45]. Although the overall volumes of these non-resonant sensors were only about μL level, they also had a few shortcomings such as low sensitivity and poor noise suppression. Thus, it is very difficult for the non-resonant PA sensors to achieve high-sensitivity monitoring of trace gases. Therefore, resonant PA sensors have attracted considerable interest during recent years. Mao et al. reported a novel sensor combining an H-type PA cell with fiber-optic microphone for detecting human respiratory methane (CH4), and the final MDL was 64 parts-per-billion (ppb) [16]. In 2020, Gong
et al. optimized the size of the resonant cavity and the buffer chamber of an H-type PA cell by simulating the acoustic field distribution of the resonant cavity with the finite element analysis method [46]. The final MDL for nitrogen dioxide (NO$_2$) gas was 1.26 ppb. Although those resonant sensors achieve a higher sensitivity, the volume of the whole sensor is still very large, leading to long gas equilibrium time and large gas sampling volume. Therefore, these instruments could not be used for online measurement of trace gases in narrow space. Overall, it has been a major challenge to achieve a relatively small resonant PA cell while with a great MDL for a PAS system based on the resonant PA cell. Firstly, a relatively small PA cell has a higher resonant frequency, leading to a lower PA signal owing to the principles of PAS. Secondly, it is difficult for the demodulation system of a fiber-optic acoustic sensor working at a high frequency.

This paper reports a miniature dual-resonance PA sensor, mainly consisting of a small resonant T-type PA cell and an integrated sensor probe with a silicon cantilever beam. The resonance frequency of the miniature PA cell is matched with the first-order natural frequency of the cantilever beam to achieve dual resonance of the acoustic signal. A PAS system, employing the dual-resonance PA sensor as the prober and a high-speed spectrometer as the demodulator, has been implemented for online measurement of trace gases in narrow space. Overall, it has been confirmed that the dual-resonance PA sensor is still very large, leading to long gas equilibrium time and large gas sampling volume. Therefore, these instruments could not be used for online measurement of trace gases in narrow space. Overall, it has been 

2. Sensor design

The sketch and photo of the high-sensitivity miniature dual-resonance PA sensor are presented in Fig. 1(a) and Fig. 1(d), respectively. It consists of a PA detector, an incident optical fiber for transmitting excitation light, a PA cell with equal lengths of cylindrical buffer volume and resonant cavity, a collimator, a gas outlet and a gas inlet. The enlarged schematic diagram of the integrated PA detector is shown in Fig. 1(b). The integrated PA detector is composed of a silicon dioxide sensor head with a length of 6 mm, a silicon-on-insulator (SOI) wafer, a collimator, a gas outlet and a gas inlet. The incident fiber that transmits the excitation light is connected to the PA detector head with a length of 6 mm, a silicon-on-insulator (SOI) wafer, a collimator, a gas outlet and a gas inlet. The incident fiber that transmits the excitation light is connected to the PA detector head with a length of 6 mm, a silicon-on-insulator (SOI) wafer, a collimator, a gas outlet and a gas inlet. The incident fiber that transmits the excitation light is connected to the PA detector head with a length of 6 mm, a silicon-on-insulator (SOI) wafer, a collimator, a gas outlet and a gas inlet. The incident fiber that transmits the excitation light is connected to the PA detector head with a length of 6 mm, a silicon-on-insulator (SOI) wafer, a collimator, a gas outlet and a gas inlet. The incident fiber that transmits the excitation light is connected to the PA detector head with a length of 6 mm, a silicon-on-insulator (SOI) wafer, a collimator, a gas outlet and a gas inlet. The incident fiber that transmits the excitation light is connected to the PA detector head with a length of 6 mm, a silicon-on-insulator (SOI) wafer, a collimator, a gas outlet and a gas inlet. The incident fiber that transmits the excitation light is connected to the PA detector head with a length of 6 mm, a silicon-on-insulator (SOI) wafer, a collimator, a gas outlet and a gas inlet.
three sides can move freely. The thickness of the cantilever beam is much thinner than the thickness of the SOI wafer. Therefore, the maximum amplitude is the end of the cantilever beam. Fig. 3 (b) is the final curve for the simulated frequency response of the designed silicon cantilever, indicating a simulated first-order natural frequency of 4420 Hz. The simulated natural frequency is roughly consistent with the theoretical result calculated by Eq. (1).

4. Experimental system and results

4.1. Experimental configuration

Fig. 4 shows the principle diagram of the experiment setup for CH\textsubscript{4} measurement based on the high-sensitivity miniature dual-resonance PA sensor. It is made up of the high-sensitivity miniature dual-resonance PA sensor, a high-speed spectrometer, a super-luminescent emitting diode (SLED), a DFB laser, a circulator and a computer. The high-speed spectrometer (FBGA analyzer, BaySpec) can achieve a maximum line rate of 20 kHz with 512 pixels. The central wavelength and spectral width of the SLED (DL-CS5077, Denselight) are 1550 nm and 60 nm, respectively. The center wavelength of the DFB laser is set to 1650.9 nm to avoid the interference of water vapor in the air. The measured laser output power of the DFB laser is 10.3 mW. The DFB laser served as the pump light source is transported into the PA sensor through the collimator, and then the gas to be tested absorbs the light and generates a periodic PA signal, causing the forced vibration of the silicon cantilever. The probe light emitted by the SLED enters the F-P cavity of the acoustic sensor through the fiber circulator, and the reflected interference light is fed to the high-speed spectrometer. Finally, the output signal is acquired by the computer with a customized LabVIEW-based program.
4.2. Dual resonance of acoustic signal

In order to confirm the resonant frequency of the PA cell, a high-frequency silicon cantilever-based acoustic sensor with a relatively flat region below 4500 Hz is used. The concentration of CH\textsubscript{4} gas in the sensor is 1000 ppm. By using the second-harmonic wavelength modulation spectroscopy (2f-WMS) method \cite{48}, the frequency response of the PA sensor is shown as curve A in Fig. 5. The maximum PA signal value is generated at the modulation frequency of 2180 Hz. Therefore, the resonance frequency of the PA cell is 4360 Hz. In order to match the resonant frequency of the PA cell, the cantilever beam with the dimension of 0.8 mm × 1.12 mm × 3.9 \(\mu\)m, is used for the fiber-optic acoustic sensor. A loudspeaker is used as the sound signal generator emitting the acoustic pressure with different intensities and frequencies. The frequency of the loudspeaker is adjusted from 700 Hz to 7500 Hz, and the root mean square (RMS) value of the F-P cavity length change is continuously recorded. The sensitivity is finally calculated by multiplying the RMS by the reciprocal of the calibrated sound pressure. The curve B in Fig. 5 shows the experimental result obtained by measuring the frequency response of the silicon cantilever beam using high-speed absolute cavity-length demodulation \cite{49}. It can be clearly seen that the first-order natural frequency of the silicon cantilever is about 4375 Hz, which is almost completely matched with the resonant frequency (2\(f\)) of the designed PA cell as can be seen from curve A. The experimental result is basically coincident with the theoretical result from Eq. (1) and the simulated result by the COMSOL numerical analysis shown in Fig. 2(b). The sensitivity of the silicon cantilever-based acoustic sensor at the frequency of 4375 Hz is as high as 1110 nm/Pa, which is a significant advantage brought by the MEMS technology.

4.3. Experiments and results

Under the condition of double resonance, the frequency response of the high-sensitivity miniature dual-resonance PA sensor is tested by experiments. By using the 2 f-WMS technique, the modulation frequencies are set from 1700 Hz to 2470 Hz. The step size and sampling point are set to 5 Hz and 10, respectively. The frequency response of the high-sensitivity miniature dual-resonance PA sensor is presented in Fig. 6. It clearly shows that the peak value of the PA signal rises first and then falls with the change of the modulation frequency. When the modulation frequency is 2195 Hz, the maximum PA signal value is 1970 pm, which is significantly higher than the maximum PA signal exhibited in curve A of Fig. 5. Therefore, the working modulation frequency is set to 2195 Hz for the following experiments.

The CH\textsubscript{4} gas samples with different concentrations in the region of 25–1000 ppm are evaluated by the PAS system to test the linearity of the high-sensitivity miniature dual-resonance PA sensor. The bias drive current is controlled between 70 and 80 mA, and the step current is 0.1 mA for scanning. The final 2f-WMS spectra are shown in Fig. 7. It presents that the maximum value of the 2f-WMS signals is generated with the bias current of 75.24 mA. In addition, Fig. 8 presents the output PA signals with CH\textsubscript{4}/N\textsubscript{2} mixture concentration from 25 ppm to 1000 ppm. By the linear fitting method, the responsibility and R-squared correlation coefficient have reached 2.0 pm/ppm and 0.998, respectively, which shows that the designed high-sensitivity miniature dual-resonance PA sensor has a linear response to various concentrations of CH\textsubscript{4} gases.

The noise of the high-sensitivity miniature dual-resonance PA sensor under the background of pure N\textsubscript{2} is presented in Fig. 9(a). The MDL (1\(\sigma\) = 0.71 pm), corresponding to the responsibility of 2.0 pm/ppm, has reached to 355 ppb with an integration time of 1 s. The normalized noise equivalent absorption (NNEA) is used to evaluate the difference in performance between the designed sensor and the other same type sensors, and it is independent of the optical power and the type of gas. With an optical power of 10.3 mW and a detection bandwidth of 0.25 Hz, the NNEA is calculated to be 2.7 \(\times\) 10\(^{-9}\) cm\(^{-1}\) Whz\(^{1/2}\).
performances of some previously developed CH\textsubscript{4} sensors based on PAS are summarized in Table 1 for comparison. As can be seen from Table 1, the PAS sensor developed in this work has a high sensitivity while with a minimum cavity volume. Meanwhile, the sensitivity of the present gas sensor could be further improved by using amplified near infrared laser or mid-infrared laser sources.

An Allan-Werle analysis [54–57] has been realized by filling the designed sensor with pure N\textsubscript{2} and continuously measuring the PA signals for a long time. The Allan-Werle deviation calculated under the pure N\textsubscript{2} background is gained and presented in Fig. 9(b). It shows that the deviation curve nearly meets the 1/√t relationship, implying that the PAS system is mainly affected by the white noise during the measurement time. The Allan-Werle deviation presents that the MDL can reach to 35.6 ppb with an averaging time of 100 s. In field measurement on the CH\textsubscript{4} concentration in ambient air has also been carried out to further test the performance of the sensor. We pumped the air with different humidities into the PA sensor through an air pump, and obtained the PA signals of CH\textsubscript{4} in the air corresponding to different concentrations of H\textsubscript{2}O. Fig. 10 presents the PA signals of CH\textsubscript{4} in the air with different concentrations of H\textsubscript{2}O, indicating that the H\textsubscript{2}O have a role of promoter for the PA signals of CH\textsubscript{4}, and the promoting effect is stronger with the increase of concentration of H\textsubscript{2}O. By the linear fitting method, the slope, intercept and linearity are obtained as 3.2 × 10\textsuperscript{-4}, 3.66 ± , and 0.98, respectively. Therefore, the concentration of CH\textsubscript{4} in the air can be calculated to be 1.83±0.06 ppm, which is in the range from 1.76 ppm to 3.37 ppm found in previous literatures [17,50,58–60].

5. Conclusions

In this work, a high-sensitivity miniature dual-resonance PA sensor is reported. This sensor consists of a miniature T-type resonant PA cell and an integrated PA detector based on a silicon cantilever beam. The resonance frequency of the miniature PA cell is matched with the first-order natural frequency of the cantilever beam to achieve double resonance. The volume of the designed T-type PA cell is only about 2.26 cubic centimeters. The width, length and thickness of the cantilever processed on SOI wafer by MEMS technology are 0.8 mm, 1.12 mm, and 3.9 µm, respectively. The first-order natural frequency of the silicon cantilever is about 4375 Hz, which is in general agreement with the theoretical and simulation result. A PAS system, employing the dual-resonance PA sensor as the prober and a high-speed spectrometer as the demodulator, has been implemented for high-sensitivity CH\textsubscript{4} sensing. The CH\textsubscript{4} gas samples with different concentrations in the region of 25–1000 ppm are measured. The responsibility and R-squared correlation coefficient are 2.0 pm/ppm and 0.998, respectively. The MDL can reach up to 35.6 ppb with an average time of 100 s according to the Allan-Werle deviation analysis. With an optical power of 10.3 mW and a detection bandwidth of 0.25 Hz, the corresponding NNEA is calculated

![Fig. 8. The output PA signal with CH\textsubscript{4}/N\textsubscript{2} mixture concentration from 25 ppm to 1000 ppm.](image)

![Fig. 9. (a) The noise of the high-sensitivity miniature dual-resonance PA sensor under the background of pure N\textsubscript{2}. (b) The Allan-Werle calculated under the pure N\textsubscript{2} background.](image)

![Fig. 10. The PA signals of CH\textsubscript{4} in the air with different concentrations of H\textsubscript{2}O.](image)

| Technology           | Laser wavelength (nm) | Cavity volume (cm\textsuperscript{3}) | MDL @ IT (ppb) | NNEA (W cm\textsuperscript{-1} Hz\textsuperscript{1/2}) | Ref.       |
|----------------------|-----------------------|----------------------------------------|----------------|---------------------------------|-----------|
| Differential PAS     | 3200                  | 15.33                                  | 3600 @ 1 s     | not stated                      | [4]       |
| CEPAS                | 1650.96               | 4.19                                   | 1230 @ 10 s    | not stated                      | [13]      |
| All-optical PAS      | 1650.96               | 205                                    | 64 @ 30 s      | not stated                      | [16]      |
| Differential PAS     | 1650.96               | 33.25                                  | 36.45 @ 1 s    | 4.42 × 10\textsuperscript{-10}  | [50]      |
| MR-PAS               | 1653.7                | 222                                    | 200 @ 400 s    | 2.9 × 10\textsuperscript{-9}    | [51]      |
| LWIR-PAS             | 7760                  | not state                              | 7 @ 1 s        | 5 × 10\textsuperscript{-9}      | [72]      |
| QEPAS                | 7707                  | not state                              | 18 @ 0.1 s     | not stated                      | [53]      |
| Dual-resonance PAS   | 1650.96               | 2.26                                   | 355 @ 1 s      | 2.7 × 10\textsuperscript{-8}    | [This paper] |
to be 2.7 × 10⁻⁹ cm⁻¹ WHz⁻¹/². The PAS sensor developed in this work has demonstrated a high sensitivity while with a very small cavity volume, showing great potential for trace gas sensing in sub cubic centimeter-level spaces.

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**Declaration of Competing Interest**

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Data availability**

The data that has been used is confidential.

**References**

[1] M.B. Pushkarsky, I.G. Dunayevsky, M. Prasanna, A.G. Tsekoun, R. Go, C.K. N. Patel, High-sensitivity detection of TNT, Proc. Natl. Acad. Sci. USA 103 (52) (2006) 19630-19634.

[2] M.M.W. van Herpen, A.K.Y. Ngai, S.E. Bisson, J.H.P. Hackstein, E.J. Woltering, F.J.M. Harren, Optical parametric oscillator-based photoacoustic detection of CO₂ at 4.23 μm allows real-time monitoring of the respiration of small insects, Appl. Phys. B 82 (4) (2006) 665-669.

[3] Yang, M.Y., He, L., Zhang, X.Y., Xu, J., Zhang, R., Sun, F.K., Tittel, Ultra-high sensitive acetylene detection using quartz-enhanced photoacoustic spectroscopy with a fiber amplified diode laser and a 30.72 kHz quartz tuning fork, Appl. Phys. Lett. 110 (3) (2017), 031107.

[4] H. Zheng, M. Lou, L. Dong, H. Wu, W. Ye, X. Yin, C.S. Kim, M. Kim, W.B. Bewley, C.D. Merritt, C.L. Canedy, M.V. Warren, L. Vurgaftman, J.R. Meyer, F.K. Tittel, Compact microwave probe module for methane detection incorporating interband cascade light emitting device, Opt. Express 25 (14) (2017) 16761-16770.

[5] W. Ren, A. Parooz, D.F. Davidson, B.K. Hanson, CO concentration and temperature sensor for combustion gases using quantum-cascade laser absorption near 4.7 μm, Appl. Phys. B 107 (3) (2012) 849-860.

[6] Y. Cao, W. Jin, H.L. Hu, J. Ma, Miniature fiber tip photoacoustic spectrometer for trace gas detection, Opt. Lett. 38 (4) (2013) 434-436.

[7] J. Li, W. Chen, B. Yu, Recent progress on infrared photoacoustic spectroscopy techniques, Appl. Spectrosc. Rev. 46 (6) (2011) 440-471.

[8] M.E. Webber, M. Pushkarsky, C.K.N. Patel, Fiber-amplifier-enhanced photoacoustic spectroscopy with near-infrared tunable diode lasers, Appl. Opt. 42 (12) (2003) 2119-2126.

[9] W. Jin, Y. Cao, F. Yang, H.L. Hu, Ultra-sensitive all-fiber photothermal spectroscopy with large dynamic range, Nat. Commun. 6 (2015) 6767.

[10] K. Chen, Z. Yu, Z. Gong, Q. Yu, Lock-in white-light-interferometry-based all-optical photoacoustic spectrometer, Opt. Lett. 43 (20) (2018) 5038-5041.

[11] Zhang, Q. Wang, W. Zhang, H. Wei, Y. Li, W. Ren, UltraseNSitive acetylene detection in a high-finesse cavity with Pound-Freder-DraHL locking, Opt. Lett. 44 (8) (2019) 1924-1927.

[12] Z. Wang, H. Wei, Y. Li, R. Kan, W. Ren, Active modulation of infrared cavity laser intensity with the Pound-Freder-DraHL locking for photoacoustic spectroscopy, Opt. Lett. 45 (5) (2020) 1148-1151.

[13] Y. Jiao, H. Fan, Z. Gong, K. Yang, F. Shen, K. Chen, L. Mei, W. Peng, Q. Yu, Trace CH₄ gas detection based on an integrated spherical photoacoustic cell, Sci. Adv. 11 (11) (2021) 4907.

[14] M.W. Sigrist, Trace gas monitoring by laser photoacoustic spectroscopy and related techniques (plenary), Rev. Sci. Instrum. 74 (1) (2003) 486-490.

[15] S. Schlit, L. Thivenaz, M. Niklès, L. Emmenegger, C. Hüglin, Ammonia monitoring at trace level using photoacoustic spectroscopy in industrial and environmental applications, Spectrochim. Acta A 60 (14) (2004) 3259-3268.

[16] X. Mao, P. Zheng, X. Wang, S. Yuan, Breath methane detection based on all-optical photoacoustic spectrometer, Sens. Actuators B 239 (2017) 1257-1260.

[17] Y. Gong, T. Gao, L. Mei, K. Chen, Y. Chen, B. Zhang, W. Peng, Q. Yu, Pbb-level detection of methane based on an optimized T-type photoacoustic cell and a NIR diode laser, Photoacoustics 21 (2021), 100216.

[18] S.L. Firebaugh, K.F. Jensen, M.A. Schmidt, Miniaturization and integration of photoacoustic detection, J. Appl. Phys. 92 (2002) 1555.

[19] A.V. Gorelik, A.L. Uslievich, F.N. Nikonovich, M.P. Zakharich, V.A. Firago, N.S. Kazakov, V.S. Starovoitov, Miniaturized resonant photoacoustic cell of inclined geometry for trace-gas detection, Appl. Phys. B 100 (2) (2010) 283-289.
acoustic resonator and a lock-in white-light interferometry demodulation algorithm, J. Quant. Spectrosc. Radiat. Transf. 253 (2020), 107136.

[47] K. Chen, B. Yang, M. Guo, H. Deng, B. Zhang, S. Liu, C. Li, R. An, W. Peng, Q. Yu, Fiber-optic photoacoustic gas sensor with temperature self-compensation, Opt. Lett. 45 (8) (2020) 2458–2461.

[48] L. Mei, S. Svanberg, Wavelength modulation spectroscopy–digital detection of gas absorption harmonics based on Fourier analysis, Appl. Opt. 54 (9) (2015) 2234–2243.

[49] Y. Yang, Y. Wang, K. Chen, Wideband fiber-optic Fabry-Perot acoustic sensing scheme using high-speed absolute cavity length demodulation, Opt. Express 29 (5) (2021) 6768–6779.

[50] H. Xiao, J. Zhao, C. Sima, P. Lu, Y. Long, Y. Ai, W. Zhang, Y. Pan, J. Zhang, D. Liu, Ultra-sensitive ppb-level methane detection based on NIR all-optical photoacoustic spectroscopy by using differential fiber-optic microphones with gold-chromium composite nanomembrane, Photoacoustics 26 (2022), 100353.

[51] K. Liu, J. Mei, W. Zhang, W. Chen, X. Gao, Multi-resonator photoacoustic spectroscopy, Sens. Actuators B 251 (2017) 632–636.

[52] X. Zhang, L. Liu, Y. Liu, L. Zhang, X. Yin, H. Huan, T. Xi, X. Shao, Detectors for gas-phase photoacoustic spectroscopy: a review, Microw. Opt. Technol. Lett. (2022) 1–10.

[53] A. Elefante, M. Giglio, A. Sampaolo, G. Menduni, P. Patimisco, V.M.N. Passaro, H. Wu, H. Rossmadl, V. Mackowiak, A. Cable, F.K. Tingel, L. Dong, V. Spagnolo, Dual-gas quartz-enhanced photoacoustic sensor for simultaneous detection of methane/nitrous oxide and water vapor, Anal. Chem. 91 (20) (2019) 12866–12873.

[54] Z. Gong, Y. Chen, T. Gao, K. Chen, Y. Jiao, M. Guo, B. Zhang, S. Liu, L. Mei, W. Peng, Q. Yu, Parylene-C diaphragm-based low-frequency photoacoustic sensor for space-limited trace gas detection, Opt. Laser Eng. 134 (2020), 106288.

[55] Z. Gong, K. Chen, Y. Yang, X. Zhou, Q. Yu, Photoacoustic spectroscopy based multi-gas detection using high-sensitivity fiber-optic microphones with low-chromium composite nanomembrane, Photoacoustics 26 (2022), 100353.

[56] M. Guo, K. Chen, C. Li, L. Xu, G. Zhang, N. Wang, C. Li, F. Ma, Z. Gong, Q. Yu, High-sensitivity silicon cantilever-enhanced photoacoustic spectroscopy analyzer with low gas consumption, Anal. Chem. 94 (2) (2022) 1151–1157.

[57] P.O. Werle, R. Mücke, F. Slemr, The limits of signal averaging in atmospheric trace-gas monitoring by tunable diode-laser absorption spectroscopy (TDLAS), Appl. Phys. B 57 (2) (1993) 131–139.

[58] B.B. Jackson, E.I. Solomon, J.G. Canadell, M. Caronnel, C.B. Field, Methane removal and atmosphere restoration, Nat. Sustain. 2 (6) (2019) 436–438.

[59] A. Elefante, G. Menduni, H. Rossmadl, V. Mackowiak, M. Giglio, A. Sampaolo, P. Patimisco, V.M.N. Passaro, V. Spagnolo, Environmental monitoring of methane with quartz-enhanced photoacoustic spectroscopy exploiting an electronic hygrometer to compensate the H$_2$O influence on the sensors signal, Sensors 20 (10) (2020) 2935.

[60] A.A. Kosterev, Y.A. Bakhirkin, F.K. Tittel, S. McWhorter, B. Ashcraft, QEPAS methane sensor performance for humidified gases, Appl. Phys. B 92 (1) (2008) 103–109.

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