All-optical non-resonant photoacoustic spectroscopy for multicomponent gas detection based on aseismic photoacoustic cell

Lujun Fu, Ping Lu, Yufeng Pan, Yi Zhong, Chaotan Sima, Qiang Wu, Jiangshan Zhang, Lingzhi Cui, Deming Liu

A Wuhan National Laboratory for Optoelectronics (WNLO) and National Engineering Research Center for Next Generation Internet Access System, School of Optical and Electronic Information, Huazhong University of Science and Technology, Wuhan 430074, China
B Shenzhen Huazhong University of Science and Technology Research Institute, Shenzhen 518000, China
C Wuhan OV Optical Networking Technology Co., Ltd., Wuhan 430073, China
D Faculty of Engineering and Environment, Northumbria University, Newcastle Upon Tyne NE1 8ST, United Kingdom
E Department of Electronics and Information Engineering, Huazhong University of Science and Technology, Wuhan 430074, China
F State Key Laboratory of NBC Protection for Civilian, Beijing 102205, China

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ABSTRACT
An all-optical non-resonant photoacoustic spectroscopy system for multicomponent gas detection based on a silicon cantilever optical microphone (SCOM) and an aseismic photoacoustic cell is proposed and demonstrated. The SCOM has a high sensitivity of over 96.25 rad/Pa with sensitivity fluctuation less than ±1.56 dB between 5 Hz and 250 Hz. Besides, the minimal detectable pressure (MDP) of the sensor is 0.55 μPa·Hz^1/2 at 200 Hz, which indicates that the fabricated sensor has high sensitivity and low noise level. Six different gases of CO₂, CO, CH₄, C₂H₆, C₂H₄, C₃H₈ are detected at the frequency of 10 Hz, whose detection limits (3σ) are 62.66 ppb, 929.11 ppb, 212.94 ppb, 1153.36 ppb and 417.61 ppb, respectively. The system achieves high sensitivity and low detection limits for trace gas detection. In addition, the system exhibits seismic performance with suppressing vibration noise by 4.5 times, and achieves long-term stable operation. The proposed non-resonant all-optical PAS multi-component gas detection system exhibits the advantages of anti-vibration performance, low gas consumption and long term stability, which provides a solution for working in complex environments with inherently safe.

1. Introduction

In consideration of the complexity of the application environment where many components are existed, the actual process requires multi-component gas detection, and the content of each component gas needs to be monitored [1,2]. For example, the online detection of the dissolved gases concentration in oil of transformer is always an important characteristic to discriminate the transformer operation status [3,4]. Therefore, the technology of simultaneous detection of multi-component gas is particularly important. Tunable diode laser absorption spectroscopy (TDLAS) [5,6] and photoacoustic spectroscopy (PAS) [7–10] has been widely studied due to their specific selectivity, high sensitivity and fast response, by using absorption spectroscopy to detect trace gases. For TDLAS technology, photodetector (PD) is required. It is necessary to use high-power lasers to achieve lower gas detection limits for TDLAS. And to detect different gases, lasers of different wavelength are required. So higher requirements are put forward for PDs in TDLAS. However, only the magnitude of sound pressure needs to be detected in PAS. Therefore, PAS has unique advantages in multi gas detection.

PAS is an important technology to realize trace gas detection based on photoacoustic effect. It has the advantages of high sensitivity, high selectivity, large dynamic detection range and real-time online monitoring. It plays an important role in trace gas detection. Various kinds of photoacoustic spectral gas detection structures have been reported such as T-type cell [11,12], H-type resonant PAS [13–15], two channel...
differential resonant PAS [16–18] and the quartz-enhanced photoacoustic spectroscopy (QEPAS) [19,20]. The resonant structure has higher detection sensitivity via resonant amplifying. However, the photoacoustic signal could be unstable while the resonant frequency drift in complex application environments. As for QEPAS, the long-term instability also exist while working at the resonant frequency of 32.7 kHz [20,21]. Although beat frequency QEPAS can effectively suppress the impact of sensitivity drift near the resonant frequency, the experimental system is complicated [22]. And laser sources are usually used in these structures. However, due to the narrow tunable range of the near-infrared tunable laser and the coincidence of the gas in near-infrared spectrum, a single near-infrared tunable laser is rarely used in the detection of multi-component gases [23]. Besides, a sensitive multi-gas analyzer based on multiple lasers is complicated and costly. Though high sensitive microphone is beneficial for improving system response because of their high sensitivity to detect acoustic pressure, it’s also sensitive to external vibration in PAS gas detection, which brings difficulties to applied in the actual complex environment with high stability [8]. Therefore, the seismic resistant PAS system for multicomponent gas detection is urgently demanded.

In this work, a non-resonant PAS based on a silicon cantilever optical microphone (SCOM) and an aseismic PAC structure is proposed and demonstrated for multicomponent gas detection. A Fabry-Perot interference (FPi)-based low-frequency SCOM based on the Micro-Electromechanical systems (MEMS) technology is designed and fabricated. Experiments show that the fabricated SCOM has a strong response at low frequency, which exhibit higher sensitivity than traditional diaphragm sensors [24–26]. The pressure responsivity is measured to be over 96.25 rad/Pa with sensitivity fluctuation less than ± 1.56 dB between 5 Hz and 250 Hz. And the minimal detectable pressure (MDP) of the sensor is 0.55 μPa Hz\(^{-1/2}\) at 200 Hz. The noise performance of the SCOM is far superior to that of commercial condenser microphones [27, 28]. The structure of PAC is theoretical designed to immune to external vibration. The vibration insensitive of the PAS is greatly improved by 4.5 times through the mechanical methods, while ensuring the miniaturization with the gas consumption of only 2.15 mL. Six different gases of CO\(_2\), CO, CH\(_4\), C\(_2\)H\(_6\), C\(_2\)H\(_4\), CH\(_2\) are detected at the designed PAS system, with the detection limits (3σ) of 62.66 ppb, 929.11 ppb, 1494.97 ppb, 212.94 ppb, 1153.36 ppb and 417.61 ppb, respectively. And the experimental results verify the system has long-term stability. The proposed non-resonant all-optical PAS multi-component gas detection system exhibits the advantages of anti-vibration performance, low gas consumption and long term stability, which provides a solution for working in complex environments with inherently safe.

2. Theoretical analysis and structure design

The signal to noise ratio (SNR) of the system determines the performance of the PAS to a large extent, and it is related to the performance of the microphone and the structure of the photoacoustic cell. The microphone based on silicon cantilever has an excellent response to the acoustic wave, so that the response can be easily affected by the external vibration disturbances due to its high sensitivity. However, the minimum detection limit of the PAS system is determined by SNR, which is affected by the external environmental noise. And SCOM is usually sensitive to external vibration but not to external sound signal since it’s usually placed in an enclosed metal cell in PAS gas detection, which brings difficulties to applied in the actual complex environment with high stability. Meanwhile the structure of the photoacoustic cell determines the intensity of the acoustic signal produced by photoacoustic effect. In order to address these issues, a vibration-insensitive photoacoustic cell structure with two chambers is proposed. One chamber is used as photoacoustic cell to generate acoustic wave, while the other is placed nearby connected with the SCOM by a micro pinhole, in which the center of gravity of the microphone’s rear cavity is changed. Compared with single chamber structure, the opposite force will be exerted on the cantilever beam in the vibration environment to resist acceleration noise.

For common photoacoustic cells, the microphone is placed in the middle of the photoacoustic cell where the top of the microphone is flush with the inner wall of the cell, as shown in Fig. 1(a). When the photoacoustic cell is around with vibration noise, for example acceleration vibration to the right, the equivalent inertial force direction of the cantilever beam itself \(F_1\) is the same with the inertial force direction of the air besides the cantilever \(F_2\) which points to the left, as shown in Fig. 1(b). It’s similar while the acceleration vibration turns to the left, where the equivalent pressures are all to the right. In this case, the photoacoustic cell inevitably introduces additional vibration noise, which is difficult to eliminate when the vibration frequency coincides with the working frequency. Though these acceleration vibration noise can be suppressed or even eliminated using the double microphone system [8], there is also another method to decrease these kinds of disturbances with a single cantilever beam microphone which greatly simplifies the photoacoustic spectroscopy system. In order to reduce the impact of external acceleration vibration noise, a vibration-resistant photoacoustic cell structure with only one microphone is designed, in which the center of gravity of the back cavity is offset, as shown in Fig. 1(c). When the photoacoustic cell is placed in the vibration noise environment, for example acceleration vibration noise to the right, the equivalent inertial force direction of the cantilever beam itself \(F_1\) is contrary with the inertial force direction of the air besides the cantilever \(F_2\). When designing the structure of the photoacoustic cell reasonably, it is possible for two opposing forces to completely cancel each other out, as shown in Fig. 1(d). The combined force caused by the cantilever beam and air inertia on the cantilever can be described as [29]:

\[
p_{\text{eff}} = a(p_{\text{can}}d + p_{\text{air}}D)
\]

(1)

where \(a\) is the magnitude of acceleration noise, \(p_{\text{can}}\) is the density of cantilever, \(d\) is the thickness of cantilever, \(p_{\text{air}}\) is the density of air in the PAC, \(D\) is the distance of the center of PAC and chamber located behind the cantilever beam. When the center of chamber is further away from cantilever compared with PAC, the value of \(D\) should be negative. In order to achieve aseismic effect, it is necessary to make the effective sound pressure \(p_{\text{eff}}\) to be zero. At this point, the spacing \(D\) should satisfy the following expression:

\[
D = -\frac{p_{\text{can}}d}{p_{\text{air}}}
\]

(2)

Because the density of cantilever and gases, and the thickness of the cantilever is already known, the spacing \(D\) can be accurately calculated by Eq. (2). According to the aseismic theory analyzed in the previous stage, a proper geometrical design of PAC has been proposed and processed to compensate the vibration noise.

3. Experimental results and discussions

3.1. Experimental results of optical microphone

An optical microphone based on silicon cantilever structure by using MEMS technology is used to detect the photoacoustic pressure. The integrated SCOM includes a silicon cantilever coated with gold, a stainless steel shell, a ceramic ferrule and an optical fiber, which builds Fabry-Perot (FP) interference cavity, as shown in Fig. 2(a). The reflection spectrum of the produced SCOM is shown in Fig. 2(b). The schematic diagram of testing equipment for obtaining reflection spectra can refer to Fig. 3(b) of Ref [26]. The free spectral range (FSR) is 3.3 nm according to the interference spectrum and the FP cavity length of the SCOM is calculated to be 360 μm. The length of FP cavity changes while photoacoustic signal is generated. The reflection spectrum of the produced SCOM shifts left and right when acoustic pressure is applied to the silicon cantilever beam. In order to accurately evaluate the performance of
the produced SCOM sensor, an acoustic experimental setup is built. For details, please refer to the section 1.2 of reference [8].

To obtain the response of the fabricated sensor, sinusoidal sound waves are applied with the frequency from 5 Hz to 250 Hz. A sinusoidal fitting is used to achieve the amplitude of demodulated phase signal, in which the results are more precise compared with the common methods such as subtraction with maximum and minimum data point or extracting peak value after fast Fourier Transform (FFT) [26]. In order to obtain the performance parameters of microphone, the noises of SCOM are detected in an anechoic chamber. The noises, frequency response...
and MDP are demonstrated in Fig. 3. The noise spectrum after FFT at anechoic chamber is shown in Fig. 3(a). The experimental data of the measured frequency response and MDP from 5 Hz to 250 Hz is demonstrated in Fig. 3(b). The experimental results indicate that the fabricated SCOM has ultra-high sound pressure sensitivity, which is above 39.67 dB re 1 rad/Pa (96.25 rad/Pa) in the range of 5 Hz and 250 Hz while the sensitivity fluctuation is less than ± 1.56 dB. The transformation relationship between the phase variation and the displacement is \( \Delta \varphi = 4\pi /\lambda - n\Delta d \), where \( \lambda \) is the wavelength which is 1.55 mm, \( n \) is the refractivity which is 1 with air, \( \Delta \varphi \) is the variation of phase, \( \Delta d \) is the variation of the cavity length [30]. The MDP at 200 Hz is calculated to be about 0.55 \( \mu \)Pa Hz\(^{-1/2} \). Table 1 lists the comparisons between our work and other reported optical acoustic sensors. It can be observed that the fabricated acoustic sensor has a relatively higher sensitivity and lower noise level, which shows that the noise level of the SCOM is far superior to that of commercial condenser microphones [27, 28].

### 3.2. PAS system design

A non-resonant all-optical cantilever enhanced PAS system is designed and fabricated by using an aseismic PAC to suppress vibration noise, as shown in Fig. 4. The system consists an infrared (IR) source with an elliptic reflector, a chopper, a turntable with different filters, a cylindrical non-resonant PAC, a SCOM, a control system and phase demodulation devices. The size of cylindrical cell is optimized with the lengths of 19 mm and diameters of 12 mm, respectively. The light source is a 30 W black-body radiation infrared light source. The intensity-modulated light is transmitted to the PAC through the filter with frequency of 10 Hz. In order to accurately obtain the photoacoustic signal in the PAC, phase demodulation and lock-in amplifier is used. The phase demodulation algorithm based on fast Fourier transform can refer to the previous work [32]. The wavelength of infrared thermal radiation broadband light source covers 3 \( \mu \)m ~ 12 \( \mu \)m. When paired with different types of filters, different gases can be detected. To measure CO, CO\(_2\), CH\(_4\), C\(_2\)H\(_6\), C\(_2\)H\(_4\), C\(_2\)H\(_2\), the parameters of the optical filters should be optimized. To avoid the influence of gases other than the gas to be tested, the three adjustable filters need to be used, and the selection of filters should follow the following principles. First, as the amplitude of the photoacoustic signal is directly proportional to the absorption coefficient of the gas absorption spectral line, it is advisable to choose the spectral line position with a high absorption coefficient, and the transmittance should be as high as possible. Second, in actual measurement, there may be multiple gases, so it is necessary to avoid strong absorption peaks of other gases as much as possible to reduce cross talk when selecting the filter for the gas to be tested. Finally, due to the fact that the gases to be tested usually contains water vapor, the position of the strong absorption peak of water vapor should be avoided within the passband range of the filters. Considering the above three criteria, the specific parameters of the mid-infrared passband filters are selected as listed in Table 2. According to the HITRAN database [33], the absorption coefficient of the six gases and H\(_2\)O are shown in Fig. 5, in which the concentration of H\(_2\)O is 100 ppm and the concentration of other gases is 1 ppm. The selected filters are annotated with arrows.

### Table 1

<table>
<thead>
<tr>
<th>Material and structure</th>
<th>Sensitivity ( \mu )Pa Hz(^{-1/2} )</th>
<th>Frequency</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phenylene sulfide membrane @ 100 Hz</td>
<td>24.1 @ 100 Hz</td>
<td>2-250 Hz</td>
<td>(24)</td>
</tr>
<tr>
<td>Phenylene sulfide membrane @ 20 Hz</td>
<td>0.65 @ 20 Hz</td>
<td>20-250 Hz</td>
<td>(25)</td>
</tr>
<tr>
<td>Gold membrane @ 100 Hz</td>
<td>10.2 @ 5 Hz</td>
<td>0.8-250 Hz</td>
<td>(26)</td>
</tr>
<tr>
<td>Stainless cantilever @ 1 kHz</td>
<td>8.5 @ 1 kHz</td>
<td>50 Hz -</td>
<td>(31)</td>
</tr>
<tr>
<td>Silicon cantilever @ 1 kHz</td>
<td>5 ( \mu )Pa Hz(^{-1/2} ) @ 1 kHz</td>
<td>50 Hz -</td>
<td>(30)</td>
</tr>
<tr>
<td>Silicon cantilever @ 1 kHz</td>
<td>0.55 @ 200 Hz</td>
<td>5-250 Hz</td>
<td>(This paper)</td>
</tr>
</tbody>
</table>

### 3.3. Experimental results

To obtain the responsiveness of each gas, single component gases of different concentrations are injected into the photoacoustic cell with mass flow controller for controlling the gas flow rate of standard gases and pure N\(_2\) gas. Six different gases of CO\(_2\), CO, CH\(_4\), C\(_2\)H\(_6\), C\(_2\)H\(_4\), and C\(_2\)H\(_2\) are detected in turn with the infrared thermal radiation light source at the modulation frequency of 10 Hz. The photoacoustic spectroscopy system is kept at atmospheric pressure and room temperature. Firstly, the PAC cell is filled with the detected gases for about one minute to replace the gas inside. Then the system is idle for half a minute, with the chopper and blackbody thermal radiation light source turned on to achieve stable optical power. Afterwards, data collection is conducted, which takes approximately 20 s. Finally, the signal is calculated and solved with the computer. Finally, the system is in standby mode and the next cycle will take 2 min. The entire detection system takes 4 min to obtain a signal for a certain concentration of gas to be tested within each cycle.

Fig. 6 shows the response of the gases with different concentrations. And a linear fit to the data yields straight line with slope of 7.791 mrad/ppm, 0.5423 mrad/ppm, 0.3173 mrad/ppm, 1.197 mrad/ppm, 0.9711 mrad/ppm for six different gases of CO\(_2\), CO, CH\(_4\), C\(_2\)H\(_6\), C\(_2\)H\(_4\) and C\(_2\)H\(_2\), respectively. To verify the linear response of the all-optical photoacoustic spectroscopy system for multi-component gas detection, the linear correlation coefficients are obtained. The linear correlation coefficients (R-square value) are calculated to be 0.9978, 0.9989, 0.9994, 0.9887, 0.9996 corresponding to CO\(_2\), CO, CH\(_4\), C\(_2\)H\(_6\), C\(_2\)H\(_4\) and C\(_2\)H\(_2\) respectively, which ensures that the response of the PAS system to gas concentration is approximately linear. The standard derivations of the background noises with 21 consecutive test data are analyzed when the PAC is completely filled with pure N\(_2\), which are 0.163 mrad, 0.168 mrad, 0.158 mrad, 0.085 mrad, 0.102 mrad and 0.0823 mrad, as shown in Fig. 7. Accordingly, detection limits (3 \( \sigma \) of CO\(_2\), CO, CH\(_4\), C\(_2\)H\(_6\), C\(_2\)H\(_4\) and C\(_2\)H\(_2\) are calculated to be 62.66 ppb, 929.11 ppb, 1494.97 ppb, 212.94 ppb, 1153.36 ppb and 417.61 ppb, respectively. Experimental results for six different gases are shown in Table 3.

For comparison, performance indicators of carbon dioxide sensors based on absorption spectroscopy are summarized in Table 4. To the best of our knowledge, the detection limit in this work is optimum among previously reported optical PAS carbon dioxide sensors so far. In order to verify the practical stability of the all optical PAS system based on aseismic structure, comparative experiment based on two structures are conducted. The test results of the aseismic structure and the normal structure with the pin hole blocked for detection of pure N\(_2\) using CO\(_2\) filter are shown in Fig. 8, which last 85 min for each test. The standard deviation of normal structures is 0.731 mrad, while the standard deviation of aseismic structure is 0.163 mrad. The standard deviation of the normal structure is about 4.5 times of aseismic structure, which reflects that the designed structure has the effect of resisting vibration. In order to confirm the stability of the produced PAS system, the test for pure N\(_2\) with CO\(_2\) filter is demonstrated as shown in Fig. 9. The test results show that the signal changes by less than 0.6% within 8 h, which indicate the system has a long-term stability.
4. Conclusions

In summary, a multicomponent gas sensor based on all-optical non-resonant photoacoustic spectroscopy with silicon cantilever optical microphone is proposed and demonstrated. A FPI-based low-frequency SCOM based on the MEMS technology is designed and fabricated. Experiments show that the fabricated SCOM has high response and low noise level at low-frequency region. The pressure responsivity is measured to be over 96.25 rad/Pa with sensitivity fluctuation less than ±1.56 dB between 5 Hz and 250 Hz. And the minimal detectable pressure (MDP) of the sensor is 0.55 μPa·Hz\(^{1/2}\) at 200 Hz. The noise performance of the SCOM is far superior to that of commercial condenser microphones [27,28]. A PAC with the gas consumption of

![Diagram of the all-optical multi-component gas detection system.](image)

**Fig. 4.** The structure of the all-optical multi-component gas detection system. (FBGA: Fiber Bragg Grating Analyzer, ASE: Amplified Spontaneous Emission Light Source, SCOM: Silicon Cantilever Optical Microphone, IR Source: Infrared Source).

<table>
<thead>
<tr>
<th>Gas</th>
<th>Central wavelength (nm)</th>
<th>Bandwidth (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO(_2)</td>
<td>4260</td>
<td>195</td>
</tr>
<tr>
<td>CO</td>
<td>4600</td>
<td>190</td>
</tr>
<tr>
<td>CH(_4)</td>
<td>3317</td>
<td>215</td>
</tr>
<tr>
<td>C(_2)H(_6)</td>
<td>3345</td>
<td>65</td>
</tr>
<tr>
<td>C(_2)H(_4)</td>
<td>10600</td>
<td>1060</td>
</tr>
<tr>
<td>C(_2)H(_2)</td>
<td>3050</td>
<td>100</td>
</tr>
</tbody>
</table>

**Table 2**
Parameters of the selected passband filters.

![Absorption coefficients of H\(_2\)O and the detected gases.](image)

**Fig. 5.** The absorption coefficients of H\(_2\)O and the detected gases: the passband of the selected filters is marked with gray background.

![Absorption coefficient graph](image)
Fig. 6. PA signals of (a) CO\textsubscript{2}, (b) CO, (c) CH\textsubscript{4}, (d) C\textsubscript{2}H\textsubscript{6}, (e) C\textsubscript{2}H\textsubscript{4} and (f) C\textsubscript{2}H\textsubscript{2} with different concentrations.

Fig. 7. The background noises with 21 consecutive test data for (a) CO\textsubscript{2}, (b) CO, (c) CH\textsubscript{4}, (d) C\textsubscript{2}H\textsubscript{6}, (e) C\textsubscript{2}H\textsubscript{4} and (f) C\textsubscript{2}H\textsubscript{2}.
only 2.15 mL based on an aseismic structure is designed and demonstrated. The detection limits (3σ) of CO₂, CO, CH₄, C₂H₆, C₃H₆ and C₄H₂ are calculated to be 62.66 ppb, 929.11 ppb, 1494.97 ppb, 212.94 ppb, 1153.36 ppb and 417.61 ppb, respectively. To the best of our knowledge, the detection limits are optimum among previously reported optical PAS carbon dioxide sensors so far. Comparative experiment based on two structures are conducted to verify the practical performance of the all-optical PAS system by using aseismic structure. The experimental results show that the designed structure has a more stable testing effect, which indicate that the signal jitter of the PAS system with the aseismic structure is reduced by 4.5 times compared with the normal structure. The proposed non-resonant all-optical PAS multi-component gas detection system exhibits the advantages of anti-vibration performance and long term stability, which provides a solution for working in complex environments.

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

No data was used for the research described in the article.

Acknowledgement

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References


Table 3
Experimental results for six different gases.

<table>
<thead>
<tr>
<th>Gas</th>
<th>Noise level</th>
<th>Slope of response (k)</th>
<th>Detection limit (3σ)</th>
<th>R-square value (R²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO₂</td>
<td>0.163 mrad</td>
<td>7.791 mrad/ppm</td>
<td>62.66 ppb</td>
<td>0.9978</td>
</tr>
<tr>
<td>CO</td>
<td>0.168 mrad</td>
<td>0.5423 mrad/ppm</td>
<td>2.173 mrad/ppm</td>
<td>0.9949</td>
</tr>
<tr>
<td>CH₄</td>
<td>0.085 mrad</td>
<td>1.137 mrad/ppm</td>
<td>212.94 ppb</td>
<td>0.9887</td>
</tr>
<tr>
<td>C₂H₆</td>
<td>0.102 mrad</td>
<td>0.2663 mrad/ppm</td>
<td>1153.36 ppb</td>
<td>0.999</td>
</tr>
<tr>
<td>C₂H₂</td>
<td>0.0823 mrad</td>
<td>0.5911 mrad/ppm</td>
<td>417.61 ppb</td>
<td>0.9996</td>
</tr>
</tbody>
</table>

Table 4
Performance indicators of carbon dioxide sensors based on absorption spectroscopy.

<table>
<thead>
<tr>
<th>Technology</th>
<th>Operating frequency</th>
<th>Wavelength region</th>
<th>Detection limit</th>
<th>Ref.</th>
</tr>
</thead>
<tbody>
<tr>
<td>QEPAS</td>
<td>20 kHz</td>
<td>Mid-infrared</td>
<td>2.4 ppm</td>
<td>[34]</td>
</tr>
<tr>
<td>QEPAS</td>
<td>12.45 kHz</td>
<td>Far-infrared</td>
<td>800 ppb</td>
<td>[35]</td>
</tr>
<tr>
<td>Resonant PAS</td>
<td>6215 Hz</td>
<td>Near-infrared</td>
<td>83 ppm</td>
<td>[36]</td>
</tr>
<tr>
<td>Resonant PAS</td>
<td>342 Hz</td>
<td>Mid-infrared</td>
<td>223 ppb</td>
<td>[37]</td>
</tr>
<tr>
<td>Non-resonant PAS</td>
<td>20 Hz</td>
<td>Mid-infrared</td>
<td>94 ppb</td>
<td>[38]</td>
</tr>
<tr>
<td>Non-resonant PAS</td>
<td>10 Hz</td>
<td>Mid-infrared</td>
<td>62.66 ppb</td>
<td>[This paper]</td>
</tr>
</tbody>
</table>

Fig. 8. Noise performance of the all optical PAS system based on normal structure and aseismic structure.

Fig. 9. The tested signals of N₂ for 8 h.
Chaotan Sima is an Associate Professor at Huazhong University of Science and Technology, China. He obtained the PhD degree at the Optoelectronics Research Centre in the University of Southampton UK in 2013. He has been awarded the Marie-Curie Fellowship in 2019 and IEEE senior member since 2021. His research interests include advanced optical gas sensing, planar waveguide devices and holey optical fiber. He has been granted over 10 projects from National Natural Science Foundation of China and the National Key Research and Development Program of China etc. He serves as an editorial member of Optical and Quantum Electronics.

Qiang Wu received the B.S. and Ph.D. degrees from Beijing Normal University and Beijing University of Posts and Telecommunications, Beijing, China, in 1996 and 2004, respectively. From 2004–2006, he worked as a Senior Research Associate in City University of Hong Kong. From 2006–2008, he took up a research associate post in Heriot-Watt University, Edinburgh, U.K. From 2008–2014, he worked as a Stokes Lecturer at Photonics Research Centre, Dublin Institute of Technology, Ireland. He is an Associate Professor / Reader with Faculty of Engineering and Environment, Northumbria University, Newcastle Upon Tyne, United Kingdom. His research interests include optical fiber interferometers for novel fiber optical couplers and sensors, nanofiber, microsphere sensors for bio-chemical sensing, the design and fabrication of fiber Bragg grating devices and their applications for sensing, nonlinear fibre optics, surface plasmon resonant and surface acoustic wave sensors. He has over 290 publications in the area of photonics and holds 10 invention patents. He is an Editorial Board Member of Scientific Reports, an Associate Editor of IEEE Sensors Journal and the Journal of Nonlinear Optical Physics & Materials, and an Academic Editor for Journal of Sensors.

Jiangshan Zhang is an Associate Professor in School of Electronic Information and Communications at Huazhong University of Science and Technology, China. He obtained the Ph.D. degree on information and communication Engineering in 2005 from Huazhong University of Science and Technology, China. His research interests include signal processing and digital communication.

Lingzhi Cui is Assistant Researcher at State Key Laboratory of NBC Protection for Civilian. She received the PhD degree at the College of Chemistry and Molecular Engineering in Peking University in 2020. Her recent research interests include optical sensing materials and optical communication devices.

Deming Liu was born in Hubei Province, China, in January 1957. He received the Graduate degree from Chengdu Institute of Telecommunication (now University of Electronic Science and Technology of China), Chengdu, China, in 1984. Currently, he is the Professor of Huazhong University of Science and Technology, Wuhan, China. His recent research interests include optical access network, optical communication devices, and fiber-optic sensors.