Simultaneous atmospheric nitrous oxide, methane and water vapor detection with a single continuous wave quantum cascade laser

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Abstract: A continuous wave (CW) quantum cascade laser (QCL) based absorption sensor system was demonstrated and developed for simultaneous detection of atmospheric nitrous oxide (N₂O), methane (CH₄), and water vapor (H₂O). A 7.73-μm CW QCL with its wavelength scanned over a spectral range of 1296.9-1297.6 cm⁻¹ was used to simultaneously target three neighboring strong absorption lines, N₂O at 1297.05 cm⁻¹, CH₄ at 1297.486 cm⁻¹, and H₂O at 1297.184 cm⁻¹. An astigmatic multipass Herriott cell with a 76-m path length was utilized for laser based gas absorption spectroscopy at an optimum pressure of 100 Torr. Wavelength modulation and second harmonic detection was employed for data processing. Minimum detection limits (MDLs) of 1.7 ppb for N₂O, 8.5 ppb for CH₄, and 11 ppm for H₂O were achieved with a 2-s integration time for individual gas detection. This single QCL based multi-gas detection system possesses applications in environmental monitoring and breath analysis.

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References and links

1. Introduction

Nitrous oxide (N\textsubscript{2}O), methane (CH\textsubscript{4}), and water vapor (H\textsubscript{2}O) are three major atmospheric greenhouse gases contributing to global warming and climate change [1, 2]. N\textsubscript{2}O has a global warming potential (GWP) of 298 (100-yr horizon) and a longer atmospheric lifetime than carbon dioxide (CO\textsubscript{2}) [1, 3]. Atmospheric N\textsubscript{2}O concentrations are increasing at a rate of ~0.7
ppbv/yr and are currently approaching a 330 ppbv concentration level [1]. CH₄ has a relatively short lifetime (~12 years) in the atmosphere compared with CO₂ and N₂O, and exhibits a GWP of 25 (100-yr horizon) with atmospheric concentrations of ~1.8 ppm [3]. H₂O is a dominant energy carrier in the atmosphere and regulates planetary temperatures through absorption and emission of radiation [1]. Considering their environmental relevance, high precision and sensitivity measurements of these three greenhouse gases are necessary to determine their sources and concentration levels, leading to a better understanding of global warming and climate change.

The most widely used method for detection of atmospheric N₂O, CH₄ and H₂O is tunable diode laser absorption spectroscopy (TDLAS) [3-9]. Nelson et al. reported a compact and fast response mid-infrared absorption spectrometer for high precision N₂O and CH₄ measurements by using two different thermoelectrically cooled, pulsed quantum cascade lasers (QCLs) and a 56-m path-length multipass gas cell. Simultaneous measurements of N₂O and CH₄ with minimum detection limits (MDLs) of 3 ppb and 7 ppb were achieved respectively near 7.8 µm with a 1-s integration time [4]. Both laboratory and open path measurements for simultaneous detection of N₂O and CH₄ using a QCL were demonstrated. MDLs of 2 ppb for N₂O and 7 ppb for CH₄ at room temperature and atmospheric pressure based on a 210-m multipass cell have been reported [3]. Sensitive ambient CH₄, CO and N₂O measurements based on a single mid-infrared difference frequency generation laser system were performed with a 5-m multipass cell [5]. A compact and portable sensor was developed for simultaneous measurements of atmospheric N₂O and CO with a 4.5-µm QCL and an open-path multipass cell (16-m path-length, atmospheric pressure). Laboratory detection limits of 0.15 ppb for N₂O and 0.36 ppb for CO were achieved at 10 Hz [6]. A QCL absorption spectrometer was reported for in situ measurements of atmospheric N₂O and CH₄ emission fluxes [7]. A compact quartz-enhanced photoacoustic spectroscopy system was developed for CH₄ and N₂O detection with a 7.83-µm QCL. MDLs of 13 ppb and 6 ppb for CH₄ and N₂O were achieved with a 1-s data acquisition time [8]. A single-QCL based absorption sensor was demonstrated for simultaneous detection of ppb-level CH₄ and N₂O by using a 7.8-µm QCL and 57.6-m multipass cell, with MDLs of 5.9 ppb and 2.6 ppb for CH₄ and N₂O, respectively [9]. Other spectroscopic methods such as open-path Fourier transform infrared spectrometry [10] and cavity ring-down spectroscopy [11] have been reported for sensitive atmospheric multi-gas detection.

In this work, we developed an absorption sensor system for simultaneous atmospheric N₂O, CH₄, and H₂O concentration measurements by using a single continuous wave (CW) distributed feedback (DFB) QCL operating at a wavelength of ~7.71 µm. A commercially available multipass cell with a compact size (32 cm long, 0.5 liters volume) was used as the multi-gas absorption cell with an effective path length of 76 m.

2. Absorption line selection

Most atmospheric gas species have their strong fundamental absorption lines in the mid-infrared spectral range, which permits sensitive and selective atmospheric gases detection in this spectral range. Fig. 1(a) shows the absorption lines of three main atmospheric gases, i.e., N₂O, CH₄, and H₂O, for wavelengths from 3 to 8.5 µm based on the HITRAN database [12]. It can be observed that the strongest absorption bands are located at ~4.5 µm for N₂O, ~3.3 µm for CH₄, and ~5.9 µm for H₂O. However, there are relatively strong absorption lines for these three gases that overlap with each other at ~7.7 µm. This spectral feature makes feasible the simultaneous sensitive detection of three gases using a single QCL, thereby simplifying the sensor system and reducing its size and cost. A high-resolution absorption spectrum of our three selected gases at a pressure of 50 Torr and a 1-m absorption length is depicted in Fig. 1(b). Three neighboring absorption lines, a N₂O line at 1297.05 cm⁻¹, a CH₄ line at 1297.486 cm⁻¹, and a H₂O line at 1297.184 cm⁻¹, are well separated from each other within a relatively small spectral range of ~0.5 cm⁻¹. This allows a mid-infrared QCL operating at ~7.7 µm to cover three absorption lines simultaneously. It should be noted that the combination of these three lines might not be the only choice for simultaneous detection of N₂O, CH₄ and H₂O, but
is based on the operating wavelength range of the QCL that was available in our laboratory. For example, a laser frequency of 1270 cm\(^{-1}\) was selected for N\(_2\)O, H\(_2\)O and CH\(_4\) detection by Aerodyne Research Inc. [13].

![Absorption lines of N\(_2\)O, CH\(_4\), and H\(_2\)O for a wide spectral range from 3 to 8.5 µm](image1)

![Absorption spectra of N\(_2\)O, CH\(_4\), and H\(_2\)O in a narrow range from 1296.95 cm\(^{-1}\) to 1297.6 cm\(^{-1}\) for specific concentrations and a 1-m path length at a pressure of 50 Torr. N\(_2\)O, CH\(_4\), and H\(_2\)O lines are shown as blue, red, and green, respectively.](image2)

Fig. 1. (a) Absorption lines of N\(_2\)O, CH\(_4\), and H\(_2\)O for a wide spectral range from 3 to 8.5 µm as vertical drop lines; (b) Absorption spectra of N\(_2\)O, CH\(_4\), and H\(_2\)O in a narrow range from 1296.95 cm\(^{-1}\) to 1297.6 cm\(^{-1}\) for specific concentrations and a 1-m path length at a pressure of 50 Torr. N\(_2\)O, CH\(_4\), and H\(_2\)O lines are shown as blue, red, and green, respectively.

3. Experimental

3.1 Characterization of QCL based TDLAS excitation source

Mid-infrared CW DFB QCLs are perfect excitation sources for laser-based gas sensor systems due to their operation in the spectral range covering most of the fundamental gas absorption lines, high optical power (>100 mW), relatively narrow linewidth, good wavelength tunability, ability to operate at room temperature and compact size [14-16]. Therefore, QCL-based gas sensor systems [17] are widely used for high sensitivity and selectivity trace gas detection in a variety of applications including environmental monitoring [18-20] and medical diagnostics [21,22]. A CW DFB-QCL (Corning Inc., New York) with a wavelength of ~7.73 µm was used as an excitation source to target the absorption lines near 1297 cm\(^{-1}\) for simultaneous multiple species gas detection. The QCL is enclosed in a high heat load (HHL) package, and the output QCL beam is collimated by an aspheric lens (f=1.87 mm) before passing through an antireflective Ge window that is used to seal the HHL package. The QCL output power and wavelength are measured using an optical power meter (NOVA II, OPHIR) and a Fourier transform infrared (FTIR) spectrometer (Nicolet 8700, Thermo Scientific), respectively. The optical power and wavenumber of the CW DFB QCL for different operating temperatures and injection currents are presented in Figs. 2(a) and 2(b), respectively. Fig. 2(b) shows that a wavenumber of ~1297 cm\(^{-1}\), corresponding to the optimum target absorption spectral region for simultaneous detection of N\(_2\)O, CH\(_4\), and H\(_2\)O, can be obtained at room
temperature and reduced current for this QCL. The current and temperature controlled wavelength tuning coefficients for this DFB-QCL are determined to be -0.014 cm$^{-1}$/mA and -0.09 cm$^{-1}$/°C, respectively. A QCL injection current of 240 mA combined with a 15 °C QCL operation temperature were selected for simultaneous atmospheric N$_2$O, CH$_4$ and H$_2$O concentration measurements.

3.2 TDLAS based Sensor platform

A TDLAS method combined with a long path length gas absorption cell was utilized for multiple gas detection in this work. Wavelength modulation spectroscopy with second harmonic (2f-WMS) detection technique was adopted for data generation and processing to achieve an enhanced signal-to-noise ratio. The schematic setup of the sensor system is depicted in Fig. 3. A 7.73-µm CW DFB-QCL is operated with both a temperature controller (TED 200C, Thorlabs Inc.) and a current controller (LDX 3232, ILX Lightwave). The QCL beam was optimized and focused to the center of an astigmatic multipass gas cell (AMAC-76, Aerodyne Research Inc.) using a pair of plano-convex lenses (f$_1$=50 mm and f$_2$=100 mm) and a 400-µm-diameter pinhole. A visible diode laser (λ=630 nm) was injected into the system via a flip mirror and co-aligned with the infrared beam to facilitate the beam alignment with the multipass cell. When a desired beam pattern (shown in the upper-left corner of Fig. 3) appears on the front mirror of the cell, an effective path length of 76 m (238 passes) is achieved according to the AMAC-76 design specifications. The QCL beam exiting from the multipass cell was collected by a parabolic mirror and sent to a thermoelectrically (TE) cooled mid-infrared detector (PVMI-3TE-8, Vigo System S.A.). The QCL wavelength was tuned to the desired spectral range determined in Sect. 3.1 (240 mA, 15 °C), and then scanned and modulated by combined sawtooth and sinusoidal signals from a function generator (AFG 3102, Tektronix Inc.). The output signal from the detector was sent to a lock-in amplifier for second harmonic demodulation and recorded by a DAQ device. The DC part of the detector output was also recorded by the DAQ device via a low pass filter to monitor the laser power variation. The gas sample inside the multipass cell was controlled by a pressure controller (Type 640, MKS Instruments) and a vacuum pump (N813.5, KNF).
Fig. 3. Schematic of a three-gas sensor system based on a single CW DFB QCL. M: mirror; PCL: plano-convex lens; DAQ: data acquisition; PC: personal computer.

3.3 Flow response time test

The flow response time in the multipass gas cell was evaluated for N$_2$O, CH$_4$ and H$_2$O. The multipass gas cell was initially filled with a constant concentration of N$_2$O, CH$_4$, or H$_2$O. Pure dry N$_2$ was used to flush the cell at different flow rates. During this process, the signal at the absorption line peak of N$_2$O, CH$_4$, or H$_2$O was monitored. As different flow rates were injected into the multipass gas cell, the signal variation at the selected absorption lines for N$_2$O, CH$_4$, and H$_2$O was recorded accordingly. The amplitude-normalized signal for each individual gas during the flushing process is shown in Fig. 4. From Fig. 4, it is apparent that the flushing time decreases with increasing gas flow rate, which can be explained by the fact that a larger flow rate increases the gas exchange rate in the multipass gas cell. For a fixed flow rate, for example 140 standard cubic centimeters per minute (SCCM), the response times for N$_2$O, CH$_4$ and H$_2$O detection are estimated to be 4.8 s, 4.6 s, and 11.1 s, respectively from an exponential decay curve fitting on the curves shown in Fig. 4. These time response plots reveal that the removal rates of N$_2$O and CH$_4$ are comparable, while the response time for H$_2$O is significantly longer. This could be explained by the sticky nature of water molecules [23], i.e., the surface adsorption-desorption of water molecules inside the gas pipe and multipass cell greatly reduces the exchange rate of the water molecules.
4. Individual trace gas detection

The sensor system was first evaluated for individual trace gas detection in order to determine the MDLs for N\(_2\)O, CH\(_4\), and H\(_2\)O. To this end, the CW DFB QCL wavelength was tuned to the respective N\(_2\)O, CH\(_4\), and H\(_2\)O absorption line center to measure N\(_2\)O, CH\(_4\), and H\(_2\)O concentrations individually.

4.1 N\(_2\)O detection

For N\(_2\)O detection, the QCL wavelength is tuned to the center of the target N\(_2\)O absorption line at \(\sim 1297.05 \text{ cm}^{-1}\) (240 mA, 17.2 °C). A ramp signal (2 s in period, 6 mA in amplitude) is used to control the QCL wavelength scan. A 5 kHz sinusoidal signal is used to modulate the QCL wavelength and generate a 2f signal curve along the absorption line. The 2f signal is demodulated by a lock-in amplifier with an optimum time constant of 50 ms over the selected ramp period. In order to determine the optimum operating conditions for N\(_2\)O detection, the sensor system was evaluated at different pressures inside the multipass cell and WMS modulation depths. The peak 2f signals for a fixed N\(_2\)O concentration (330 ppb) were recorded for each individual pressure-modulation-depth combination and plotted in Fig. 5(a). Optimum operating conditions of 80 Torr and 4 mA were selected for N\(_2\)O concentration measurements.

The sensor calibration is performed by diluting gas from a standard cylinder containing 2 ppm N\(_2\)O balanced by N\(_2\) with pure N\(_2\). By controlling the flow rate of each cylinder, gas mixtures with different N\(_2\)O concentration levels ranging from 0 to 2 ppm are obtained precisely and delivered to the multipass gas cell for sensor sensitivity calibration. Figure 5(b) shows the 2f signal response of the sensor system when N\(_2\)O with different step concentration is injected into the gas cell. The signal plateaus for each concentration can be distinguished clearly, and the 2f signal shows good linear relationship (\(R^2=0.99774\)) with the concentration of N\(_2\)O, indicating a sensor sensitivity of 6.142 mV/ppm.
Fig. 5. (a) Pressure and modulation depth optimization for N$_2$O detection; (b) Sensor sensitivity calibration for N$_2$O. The inset of Fig. 5(b) shows the average signal for each N$_2$O concentration level and its linear fit.

The sensor detection limit of N$_2$O was determined by passing pure N$_2$ through the multipass gas cell at its optimum operating conditions. The 2f signal was recorded continuously with a time interval of 2 s over 500 s. The signal in terms of N$_2$O concentration based on the sensor sensitivity is presented in Fig. 6(a). An Allan deviation analysis was applied to evaluate the noise behavior for N$_2$O detection as depicted in Fig. 6(b). A MDL of 1.7 ppb for N$_2$O was observed for a 2-s sampling time, corresponding to a noise level of 1.7x10^{-4} in terms of absorption. This noise level results mainly from the laser controlling electronics. An optimum MDL is estimated to be 0.3 ppb for an integration time of 100 s.

Fig. 6. (a) Measured N$_2$O concentration by passing pure N$_2$ into the multipass cell; (b) Allan deviation plot for the data shown in Fig. 6(a).

4.2 CH$_4$ detection

CH$_4$ detection is based on the strong absorption line of CH$_4$ at 1297.486 cm$^{-1}$. The QCL wavelength was tuned to the target line center (240 mA, 12.4 °C). A similar combined ramp (2 s, 10 mA) and sinusoidal signals (f=5 kHz) was applied to the CW QCL to realize laser wavelength scanning and modulation simultaneously as described in Sect. 4.1. The demodulated 2f signals at the absorption line peak with a lock-in time constant of 50 ms are plotted in Fig. 7(a) for different gas pressures in the multipass gas cell and modulation depths. According to Fig. 7(a), optimum operating conditions for the sensor system are found to be a
100-Torr pressure and 4-mA modulation depth. With these optimized sensor parameters, sensor calibration was carried out by using diluted standard CH₄ gas with different concentrations as shown in Fig. 7(b). The fitting curve in the inset of Fig. 7(b) indicates a good linear relationship (R²=0.997) between 2f signal and CH₄ concentration, with a sensitivity of 3.137 mV/ppm.

![Graph showing CH₄ concentrations and modulation depth optimization](image)

Fig. 7. (a) Pressure and modulation depth optimization for CH₄ detection; (b) CH₄ concentration response for the sensor system.

The noise level was determined by passing pure N₂ into the system and thereby subsequent monitoring the detected 2f signal in terms of CH₄ concentration at the CH₄ peak position based on the calibrated sensitivity for CH₄. Figure 8(a) shows the detected CH₄ concentration variation in the multipass gas cell over 800 s. A MDL of 8.5 ppb for CH₄ was achieved for a 2-s sampling time from the Allan deviation plot depicted in Fig. 8(b). This value can be improved to 2.5 ppb when the averaging time is increased to 50 s.

![Graph showing measured CH₄ concentrations](image)

Fig. 8. (a) Measured CH₄ concentrations as pure N₂ flows over the multipass cell; (b) Allan deviation plot for the data in Fig. 8(a).

### 4.3 H₂O detection

The sensor system was also evaluated for H₂O detection. The water absorption line at 1297.184 cm⁻¹ was selected as the target line, corresponding to the CW DFB QCL operating conditions of 240 mA and 15.7 °C. A 1-s ramp period and a 20-ms lock-in amplifier time
constant were applied for improved sensor performance. An optimum pressure of 400 Torr and modulation depth of 5.5 mA were determined for H_2O detection following the procedures described in Sect. 4.1 and 4.2. Considering the strong absorption for atmospheric H_2O, the water concentration in the multipass cell was calibrated by fitting the transmittance curve to theoretical simulations based on the HITRAN database [12]. The sensor was evaluated measuring a constant H_2O concentration generated by passing air flow over a container filled with deionized water. The results are displayed in Fig. 9(a) and reveal a measured average H_2O concentration in the multipass gas cell of 1.892%. From the Allan deviation analysis plot in Fig. 9(b), MDLs of 16 ppm with a 1-s integrating time and 11 ppm with a 2-s integrating time were obtained for H_2O measurement. An optimum MDL of 5 ppm can be estimated for an averaging time of 30 s.

![Figure 9](image)

Fig. 9. (a) H_2O measurements during a 800 s period; (b) Allan deviation analysis.

5. Simultaneous three gas detection of N_2O, CH_4, and H_2O with a single CW QCL

As described in Sect. 2, the three neighboring strong absorption lines of N_2O, CH_4, and H_2O in a narrow spectral range of 1297-1297.5 cm\(^{-1}\) are monitored for simultaneous concentration measurements of these gases with a single QCL. The sensor system is the same used for individual gas detection as described in Sect. 4. A ramp signal with larger amplitude (11 mA, 1 Hz) was applied to the QCL with the heat sink temperature set to 20 °C to cover all three absorption lines within a single continuous wavelength scan. A pressure of 100 Torr inside the multipass gas cell and a modulation depth of 4 mA were selected for optimum sensor operation. The direct output signal from the detector after a low pass filter is shown in Fig. 10(a) and the 2f signal demodulated by the lock-in amplifier with a time constant of 5 ms is depicted in Fig. 10(b) for ambient air. It is observed that these three gas lines are included with low interference within a single laser scan for both the absorption and 2f signals. In order to eliminate the effect of signal variation due to long term laser power drift, the measured 2f signal was normalized to the transmitted power as measured from the detector output in the non-absorption region. The N_2O and CH_4 sensitivity calibrations are based on the dilution of standard gases, and H_2O sensitivity is determined by dividing the normalized 2f signal by the H_2O concentration, which was obtained from the direct output curve of the detector as described in Sect. 4.3. The subsequent measurements are based on the analysis of the variation of these peaks for different gas concentration changes in a laboratory environment and ambient atmosphere, respectively.
5.1 Laboratory air component measurements

The sensor system was evaluated for simultaneous measurements of N$_2$O, CH$_4$, and H$_2$O concentrations in a laboratory environment. Measured concentration changes of N$_2$O, CH$_4$, and H$_2$O over 14 hours are displayed in Fig. 11(a). It is observed that the concentration of N$_2$O was relatively constant during this period of time, with a concentration level of $\sim$345±9.7 ppb. However, the CH$_4$ concentrations showed significant variation, from 2 ppm up to 4 ppm, especially in the early morning hours. This increase in the CH$_4$ concentration is in accordance with the typical diurnal profile exhibited by this gas species during summer time [24]. The H$_2$O concentrations were in the range of 0.86%-1.05%, with its maximum value appearing around 03:00 CDT. The average H$_2$O concentration during this period of time is found to be 0.97±0.046%. The MDLs of these three gases are analyzed for relatively stable concentration intervals within a continuous measurement period and plotted in Fig. 11(b). MDLs were found to be 6.5 ppb for N$_2$O, 23 ppb for CH$_4$, and 62 ppm for H$_2$O with a 1-s integration time. Compared with the individual gas detections described in Sect. 4, these MDLs are 3-4 times larger. This difference is mainly attributed to a larger wavelength scan range within a single ramp period of the sensor system for a 1 s acquisition time. However, with a longer averaging time of 100 s, the MDLs can be decreased to 0.4 ppb for N$_2$O, 3 ppb for CH$_4$, and 6 ppm for H$_2$O, which are appropriate for atmospheric concentration monitoring of these three species.
5.2 Atmospheric $N_2O$, $CH_4$, and $H_2O$ concentration measurements

The sensor system was also evaluated for simultaneous three gas species detection present in the ambient atmosphere on the Rice University campus. The sensor system was installed on a cart and placed outside the Laser Science Laboratory to monitor variations of atmospheric $N_2O$, $CH_4$, and $H_2O$ concentrations (Fig. 12(a)). The measured concentrations are plotted in Fig. 12(b). The experiment was conducted from 10:25 CDT to 16:35 CDT on September 24, 2014. At the end of the measurement period, pure $N_2$ was filled into the multipass cell to verify the zero-background signal. Concentration fluctuations were observed during atmospheric monitoring of $N_2O$, $CH_4$, and $H_2O$, especially for $H_2O$ concentrations. For most of the sampling interval, the $N_2O$ concentrations were in the range of 300-350 ppb, with an average value of $323 \pm 11$ ppb. $CH_4$ concentrations were measured to be up to 4 ppm for the first 20 minutes (as reported in Sect. 5.1) of the monitoring period and then dropped gradually to its typical background level of $\sim 1.87$ ppm. The $H_2O$ concentrations were found to be between 0.89% and 1.19%, with an average concentration of $0.99 \pm 0.039\%$. In order to examine the validity of these results, $H_2O$ mixing ratios were calculated for the period of measurements based on local meteorological conditions (e.g. relative humidity, temperature and pressure). According to these calculations, $H_2O$ concentration ranged between 0.74% and 0.98% with a mean value of $0.91 \pm 0.061\%$ for the period between 10:25 CDT and 16:35 CDT on September 24, 2014. Although the estimated $H_2O$ concentrations were slightly lower than those detected by the sensor system, good agreement was observed between both determinations. Additionally, detected $N_2O$ and $CH_4$ levels are in accordance with the
corresponding atmospheric concentrations of these species [1, 3]. As shown in Fig. 12(b), pure N\textsubscript{2} flowing into the gas cell leads to a rapid decrease in the concentration signals of these three gas species.

Fig. 12. (a) Single CW QCL based N\textsubscript{2}O, CH\textsubscript{4} and H\textsubscript{2}O sensor system; (b) Measurement results of simultaneous three gas concentrations monitoring in the atmosphere for a 6 hour time duration.

6. Conclusions

A sensitive and selective sensor system based on a single CW DFB-QCL was demonstrated for simultaneous detection of N\textsubscript{2}O, CH\textsubscript{4} and H\textsubscript{2}O. The system was based on TDLAS and 2f-WMS detection methods. A CW DFB-QCL with a wavelength of ~7.73 µm was employed to cover three strong absorption lines for different gas species within a narrow spectral range. An astigmatic multipass Herriott gas cell with an effective path length of 76 m was used to enhance the gas absorption in a compact space (0.5 liters). The sensor system was first evaluated for individual N\textsubscript{2}O, CH\textsubscript{4}, and H\textsubscript{2}O detection, respectively, with the QCL wavelength tuned to each gas absorption line center. MDLs of 1.7 ppb for N\textsubscript{2}O, 8.5 ppb for CH\textsubscript{4}, and 11 ppm for H\textsubscript{2}O with an integration time of 2 s were achieved for individual detection of these species. Subsequently, the sensor system was evaluated for simultaneous N\textsubscript{2}O, CH\textsubscript{4}, and H\textsubscript{2}O detection based on this single QCL. Measurement results for both laboratory and atmospheric concentration changes of these three gases were presented and discussed. This system shows the advantage of simultaneous high-sensitivity multiple gas species detection with reduced cost and size.

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