APPLICATION OF BALANCED DETECTION TO ABSORPTION MEASUREMENTS OF TRACE GASES WITH ROOM-TEMPERATURE, QUASI-CW QC LASERS

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ABSTRACT

Distributed feedback quantum cascade (QC) lasers are expected to form the heart of the next generation mid-IR laser absorption spectrometer, especially as applied to measurements of trace gases in a variety of environments. Incorporation of room temperature-operable, single mode QC lasers will result in very compact and rugged sensors for real world applications. We report preliminary results on the performance of a laser absorption spectrometer using a QC laser operating at room temperature in quasi-cw mode in conjunction with balanced ratiometric detection. We have demonstrated sensitivities for N2O (10 parts in 10^6 for a 1 m path (ppmv-m)) and NO (520 parts in 10^9 for a 1 m path (ppbv-m)) at 5.4 μm. System improvements are described which are expected to result in two orders of magnitude increase in sensitivity.

OCIS codes: 010.1120, 120.1740, 140.3070, 300.1030, 300.6260
1. INTRODUCTION

The advent of quantum cascade (QC) lasers is expected to enable a new generation of highly sensitive trace gas sensors that will be routinely operable in the field. QC lasers operate at or near room temperature in quasi-cw mode with peak optical power in the 10 to 100 mW range. Distributed feedback versions of these lasers operate on a single longitudinal mode. These lasers have been fabricated throughout the midinfrared chemical fingerprint region from 4.6 to 13 µm. Laser absorption spectrometers achieve the highest sensitivity by operating in this region. Thus, sensors using QC laser sources offer the promise of compact and highly adapted devices for routine field deployment, in contrast to sensors using alternative, existing mid-IR sources. In this paper, we report on initial work we have undertaken to couple QC laser technology with highly sensitive balanced ratiometric detection technology.

Over the past 15 years, semiconductor laser absorption spectrometers have been developed for high sensitivity detection and monitoring of various trace species. Instruments with the highest sensitivity operate in the midinfrared, the region in which molecular linestrengths are the largest. To access this region, laser absorption spectrometers have been developed using lead salt diode lasers. Although these sensors have achieved high sensitivity, several aspects of lead salt lasers result in a complex instrument design or limit routine field use. Chief among these characteristics are that these lasers operate cw at cryogenic temperatures and that these lasers are available only as Fabry-Perot designs.

An alternate technique to access the midinfrared spectral region is to use difference frequency generation (DFG). Sensors based on DFG sources have higher power demands and are
more complex than single laser sensors. The output power is critically dependent on maintaining phase matching or quasi phase matching conditions between the overlapping beams in the crystal. Output powers are approaching the mW regime. Recent work has demonstrated integrated spectrometers operating over the 3.0 to 5.5 µm region.9

Robust and field-worthy laser absorption spectrometers have been demonstrated using near infrared diode lasers. These lasers operate at room temperature and are available in DFB architecture, and have been matured by years of development by the telecommunications industry. Many examples of field and airborne demonstrated sensors are available.10-12 Good sensitivity is achieved when combined with ultrasensitive detection techniques such as frequency modulation (FM) or balanced ratiometric detection (BRD). Ultimate chemical sensitivity can be limited because combination and overtone bands are monitored which have concomitantly weaker linestrengths than those corresponding to fundamental absorption bands.

Quantum cascade lasers achieve gain via the transition of electrons between two excited states in the conduction band of a coupled quantum well structure.1 Inversion is created by engineering the lifetimes of the states involved. The paired electron injection and active well regions are replicated many times over (cascaded) to increase output power. QC lasers can be operated in cw mode at temperatures up to 170 K and in quasi-cw mode (duty cycle of <1%) at room temperature. The output wavelength is determined by the thickness of the active region and is independent of band gap. QC lasers can be fabricated at any wavelength from 4 to 11 µm using AlInAs/InGaAs lattices on InP. The advent of QC lasers enables a new generation of laser-based
sensors which maintains the sensitivity of lead salt laser sensors and preserves the robustness and ease of operation of near-IR diode laser sensors.

Several groups have recently reported applications of QC lasers to trace gas sensing. Sensitive absorption spectroscopy using frequency modulation (FM) detection and a room temperature, pulsed DFB QC laser has been reported. Sensitive absorption spectroscopy has also been demonstrated with cryogenically cooled, cw QC lasers using either FM detection or photoacoustic detection techniques. Detection of isotopic composition has also been demonstrated using cryogenically cooled, cw QC lasers. In this paper, we report on our initial efforts in developing a QC laser-based trace gas sensor suitable for routine field deployment. Our work has focused on quasi-cw, room temperature operation of the laser source with high sensitivity detection achieved using the balanced ratiometric technique. We have used a breadboard spectrometer to investigate sensitivities for N₂O and NO.

2. EXPERIMENTAL CONFIGURATION

Several quantum cascade lasers operating near 5.4 µm have been examined in this work. These devices are similar to those described by Gmachl et al. in Ref. 17. In general, these lasers tune with temperature at a rate of 0.13 cm⁻¹/deg K (3.9 GHz/deg K). The tuning rate with injection current is approximately 10⁻² cm⁻¹/mA (300 MHz/mA). These QC lasers have a current threshold of approximately 1 A for room temperature operation. After a regime in which laser power increases linearly with current, these devices exhibit a characteristic emission rolloff at higher currents. These devices require a relatively high compliance voltage (~8 V), compared to other
semiconductor diode lasers. For zero bias, the devices have an effective resistance of approximately 1 kΩ which decreases to 1 Ω above threshold.

Each laser chip carrier is In-soldered onto a copper block, which serves as a heat sink and as the ground contact for the laser. A typical chip carrier contains four to six lasers. Two lasers are connected via thin wire bonds to Au-plated alumina plates bonded to either end of the copper block. Only one laser is operated at a given time. We fabricated a mount for the laser chip carrier in order to provide a controlled operating environment (see Figure 1). The chip carrier is mounted on a large thermoelectric cooler (TEC) to provide temperature control of the device. In between the carrier and the TEC is a copper-beryllium alloy plate. A layer of silicone thermal heat sink compound is used between the carrier and the plate. A thermistor is bonded to the large plate just behind the carrier block. The single stage TEC provides 55 W of cooling and was sized to enable cooling of the entire assembly to -30 C. The TEC is mounted on a water-cooled heat sink. The assembly is housed in an aluminum box to allow for purging. An antireflection-coated, fast Ge meniscus lens (12.5 mm diameter, f/0.8) is mounted on a precision five-axis translator at the front of the box to collimate the output beam.

From the perspective of developing a practical field sensor, we are interested in room temperature operation of the QC laser. This implies that the laser must be operated in pulsed mode. Two issues, both related to thermal management, constrain the design of the injection current pulse train. The pulse width is limited by the need to minimize the frequency chirp that arises from internal heating during the pulse. Pulse widths of 10 to 50 ns have been used. The duty cycle is also limited to < 1% by the need to manage the heating arising from the large current
densities impressed on the device. Typical operation occurs with a negatively biased, < 1 MHz pulse train with a 1% duty cycle (10 ns pulse width). In order to scan the laser wavelength across an absorption transition, we added a small amplitude, low frequency sawtooth current ramp to the pulse train. The two signals are combined using a bias tee.

A block diagram of the laser drive electronics is presented in Figure 2. We used a high power, pulsed laser diode driver (DLD) to create the pulse train. The DLD draws operational power from both low voltage and high voltage DC supplies. An external pulse generator supplied the pulse train, which was amplified by the DLD. The DLD was capable of producing peak output currents to 100 A. The pulse width was variable from 25 ns to 15 µs with rise and fall times of 20 ns. The pulse train frequency was variable up to 500 kHz. We typically operated with 50 ns pulses at 5 kHz for a duty cycle of <0.1%. The output of the DLD is via a low impedance copper strip transmission line. We used a precision current supply to provide the sawtooth ramp for wavelength scanning. A waveform generator provided a voltage control ramp to the current supply. This supply then produced a 50 mA current ramp at 10 Hz.

The general experimental arrangement for the spectroscopic absorption experiments is illustrated in Figure 3. The collimated laser beam exits the mount and is split into a signal and a reference beam using an Ar-coated Ge beamsplitter. The signal beam propagates through an 0.5 m electropolished, stainless steel absorption cell having ar-coated, 30 min.-wedged Ge windows. After exiting the cell, the beam is refocused onto an LN2-cooled InSb detector by a 25 mm diameter, ar-coated Ge f/1 lens. Similarly, the reference beam is refocused onto a second InSb detector using another Ge lens. Provision was made to purge the beam paths as shown. The
detectors were 2 mm diameter devices. Each detector was fitted with a cold field-of-view machined to match the f/1 collection optics. This was done to minimize the background current arising from collection of ambient radiation. An InSb camera aided collimation and alignment, and was used to image the beam in the far field.

Initial experiments were conducted by directing each detector output through a high gain current preamplifier and then into a gated integrator. The gated integrator signals were sampled, recorded and processed by a data acquisition system. The signal and reference outputs were processed to create an absorption spectrum. Spectra were averaged and then integrated to produce a real time history of the number density of the species under investigation. This dual beam detection method allowed us to investigate spectral absorbances down to ~0.5%.

For higher sensitivity, we adapted our BRD technique for use with the pulsed QC lasers and InSb detectors. The technique was originally designed by Hobbs at IBM, we have been developing the BRD for operation with cw visible and near-infrared diode lasers. To enable operation with pulsed photocurrents, we decreased the bandwidth of the BRD so that the detector responded to the average input power rather than to individual pulses. We created mathematical models of the temporal response of the BRD using the expected peak photocurrents, as the bandwidth of the detector depends on photocurrent. We used this analysis to modify the bandwidth of the integrating feedback loop of the circuit. We found a nominal bandwidth of a 5 to 10 kHz worked well with the 15 kHz pulse train.

We also modified the BRD for operation with the InSb detectors. The BRD has an internal voltage reference for reverse biasing the photodiodes. While this marginally increases the dark
current, it provides for an output current that is linear with respect to the incident photon flux. The detectors were operated with 85 mV of reverse bias. For experiments utilizing the BRD, the circuit output was amplified and bandpass filtered. Spectra were collected and averaged using a digital oscilloscope.

3. RESULTS AND DISCUSSION

3.1 Single Beam Results

Before proceeding with absorption studies, we investigated the electrical and optical pulse waveforms for our system. For the majority of the work performed here, the pulse generator was set to produce pulses of 50 ns widths at a repetition rate of 5 kHz. We used a miniature inductive pickup probe placed in the transmission line just prior to the laser to measure the actual current waveform produced by the DLD. The rise time of the inductive probe was 3.5 ns. The optical pulse was measured with a fast, high bandwidth HgCdTe detector (100 MHz) and preamplifier (20 MHz). Figure 4a shows both the current and optical waveforms. The observed current pulsewidth was 70 ns. Thus the pulse out of the DLD was somewhat broader than the input pulse. This was the minimum pulse width achievable with the DLD. The inductive probe has a transfer function of 1 V/A. The laser has a threshold of ~1 A. Thus, if we rescale the current pulse from this threshold, and normalize and overlay it with the optical pulse, we get excellent agreement in the pulse widths. These waveforms are compared in Figure 4b and illustrate that, above threshold, the laser power envelope tracks the input current pulse waveform.
3.2 Dual Beam, Direct Absorption Results

For initial absorption measurements, we used the dual beam (signal and reference channels) geometry described earlier but without the BRD circuit. We chose to monitor the P24E line of the $^{1}10$ band of N$_2$O (1859.31 cm$^{-1}$; 5.3783 µm). Given a current tuning parameter and the linestrength of the monitored transition (along with the pathlength and temperature), the software averages a specified number of laser sweeps, subtracts a linear baseline, integrates the lineshape, and reports a number density in real time. We calibrated the current tuning rate of the laser using an uncoated Ge flat (0.5 cm thick). The current tuning rate was measured to be 330 MHz/mA or 0.011 cm$^{-1}$/mA.

In the first experiment, the cell was filled with 48 Torr N$_2$O and the pressure was then reduced in steps. A plot of the laser-determined N$_2$O number density versus the manometer-measured number density is presented in Figure 5. Example absorption spectra are presented in Figures 6 and 7. The spectrum in Figure 6 was acquired for 48.4 Torr N$_2$O and is an average of 100 scans. The peak absorption is 0.157 and the rms signal-to-noise ratio (SNR) is 120 which implies a minimum detectable absorption of $1.3 \times 10^{-3}$. This minimum detectable absorption corresponds in turn to a detectivity of approximately 260 ppmv-m. These results are typical of the detectivity that can be achieved without any special noise reduction techniques.

We also demonstrated detection of NO by monitoring the closely spaced grouping of six lines of the P branch of the fundamental: P5.5e at 1857.268 cm$^{-1}$ (5.3843 µm) and P5.5f at 1857.280 cm$^{-1}$ (5.3842 µm). We used a precision mixture of 95 ppmv NO in N$_2$ for the majority of our work. A plot of the laser-determined NO number density versus the manometer-measured
number density is presented in Figure 7. The smallest peak absorption measured this way was
0.008 for a 10 Torr sample of the mix. The SNR was ~3 which implies a minimum detectable
absorption of $2 \times 10^{-3}$. The corresponding detectivity is approximately 200 ppbv-m. In computing
number density for this plot, we have used our measured absorptions with Beer’s Law. This
procedure is not correct and leads to the curvature observed in the plot at high number densities.
This arises because of the relative spectral widths of the laser and the absorption transition and the
concomitantly varying absorption efficiency as the sample partial pressure increases. At the
highest partial pressure used, the transitions become optically dense. We return to a discussion of
this behavior in the next section.

3.3 Dual Beam, BRD Absorption Results

We next incorporated the BRD into the pulsed QC laser spectrometer. We again monitored
$\text{N}_2\text{O}$ via the P24E line and measured the BRD output as a function of gas pressure in the cell. A
plot of BRD determined number density vs the manometer number density is presented in
Figure 8. The corresponding range of peak absorption varies from 0.0225 to 0.27. The response is
linear for low concentrations but then becomes nonlinear at higher concentrations. This behavior
is a direct consequence of the magnitude of the laser bandwidth compared to the absorber
linewidth.

It is important to realize that the laser bandwidth is greater than or equivalent to the
molecular absorption linewidth (depending on the pressure broadening) under the conditions used
for this work. The large currents and high compliance voltages required for normal pulsed
operation lead to a large power dissipation within the active region. This power dissipation directly impacts the bandwidth. During a pulse, several watts of power are impressed on the active region. This results in a large temperature variation which evolves during the pulse, which induces an accompanying tuning, or chirp, of the lasing frequency. The measured absorption linewidth is a convolution of the molecular linewidth and effective laser bandwidth averaged over the pulse. The effective laser bandwidth can be thought of as the instantaneous bandwidth averaged over the pulse duration. Laser bandwidth thus depends on operating temperature, current, pulsewidth, and to a lesser extent, pulse repetition rate. Bandwidths for cw operation at cryogenic temperatures have been measured to be ~ 50 MHz.\textsuperscript{14} For operation at 4 C with a 1 MHz pulsetrain and 11 ns pulsewidth, the bandwidth has been estimated to be 720 MHz.\textsuperscript{13} In the case of a source bandwidth that is broader than the absorber, there can be a significant departure of the measured absorption from Beer's Law behavior and it is essential to account for this in the quantitative treatment of the absorption data.

The analytical treatment of overlapping emitter and absorber line shapes follows directly from that applied to resonance absorption measurements.\textsuperscript{21,22} For a given laser peak frequency, the observed fractional absorption is given by:

\begin{equation}
A(v_{\text{laser}}) = \frac{\int f(v) \left[1 - \exp\left(-k(v)/\ell\right)\right] dv}{\int f(v) dv}
\end{equation}

where \(f(v)\) describes the laser intensity as a function of frequency, \(k(v)\) is the absorption coefficient (product of cross section and absorber concentration) as a function of frequency, and \(\ell\)
is the pathlength. Detailed analysis of a full spectral scan requires the additional integration of
\( A(\nu_{\text{laser}}) \) over the laser scan range. For present purposes, we examine the maximum absorption,
where the frequency of the peak laser intensity equals the frequency of the peak of the absorption
cross section. A rigorous treatment would use a numerical inversion method to derive \( f(\nu) \) from
the observed spectrally scanned absorption data, and would then perform forward calculations of
Eq. (1) with the exact \( f(\nu) \) and \( k(\nu) \) functions to determine absorption curves of growth. However,
a useful empirical approximation is to represent \( f(\nu) \) and \( k(\nu) \) as Gaussian functions, leading to a
convenient analytical solution:\textsuperscript{22}

\[
A(\alpha) = \frac{\int_{-\infty}^{\infty} \exp\left[-(\omega/\alpha)^2\right] \left[1 - \exp\left(-k_0\ell \exp(-\omega^2)\right)\right] d\omega}{\int_{-\infty}^{\infty} \exp\left(-(\omega/\alpha)^2\right) d\omega}
\]

(2)

and

\[
A(\alpha) = \sum_{n=1}^{\infty} (-1)^n \frac{(k_0\ell)^n}{n!(1+n\alpha^2)^{1/2}}
\]

(3)

where \( \omega = \frac{2(\ln 2)^{1/2}(\nu-\nu_o)/\Delta \nu_{\text{absorber}} \cdot \alpha = \frac{\Delta \nu_{\text{laser}}}{\Delta \nu_{\text{absorber}}} \) and \( k_o \) is the absorption coefficient at the
line center, \( \nu_o \). The Gaussian representation of the absorption line will, of course, lead to an
underestimate of the absorption for pressure-broadened Lorentzian lines, however this error is not
large over the range of our data.
The experimentally observed peak absorptions and N\textsubscript{2}O optical depths (k\textsubscript{0}\ell) are plotted in Figure 9. Here each N\textsubscript{2}O optical depth is determined from the N\textsubscript{2}O pressure, the peak absorption cross section, and the path length. As is also illustrated in Figure 9, the observed values are well below those expected for Beer's Law. The curve passing through the data points was determined by solution of Eq. (3) using the calculated Voigt line width for each N\textsubscript{2}O optical depth and using \(\Delta v\textsubscript{laser} = 0.057 \text{ cm}^{-1} (1.7 \text{ GHz})\). The only free parameter in the fit is the effective bandwidth of the laser, which is determined to a tolerance of ±10%. Since the experiments were performed using different pressures of pure N\textsubscript{2}O to obtain different optical depths, the predicted absorption value at each optical depth represents a different absorber linewidth and hence a different A versus k\textsubscript{0}\ell curve of growth. Using these predicted curves of growth to determine the N\textsubscript{2}O optical depth corresponding to each observed peak absorption, we find the optical depths determined from the absorption data correlate well with the those determined from the N\textsubscript{2}O pressures, as shown in Figure 10. The line in Figure 10 is a least squares fit with slope = 1.01 ± 0.03 and intercept = 0 ± 0.09. The increased scatter at large optical depth may be due in part to the increasing importance of collisional line broadening at these N\textsubscript{2}O pressures (∼0.1 atm) and the consequent departure of the absorber line shape from the Gaussian representation. However, the line shape convolution model clearly provides a reliable method for determining the absorption curves of growth for these laser operating characteristics.

We have used the experimental spectrum presented in Figure 6 to estimate the actual laser bandwidth for our operating conditions. From modeling of the P24E line using HITRAN96\textsuperscript{,23} the Doppler width of the line is 0.0035 cm\textsuperscript{-1} (0.11 GHz); the Lorentzian width due to collisional
broadening (48.4 Torr) is 0.0093 cm\(^{-1}\) (0.28 GHz). The Voigt linewidth is 0.011 cm\(^{-1}\) (0.32 GHz). The experimental observed linewidth is 0.099 cm\(^{-1}\) (3.0 GHz). To determine the laser spectral intensity, we convolved an initial guess of the laser profile with a HITRAN-calculated absorption profile and compared the result to the experimental spectrum of Figure 6. The difference in the calculated and observed absorption spectra was minimized using a least squares algorithm by iterating the laser profile. In this way, we calculated the laser spectral intensity, which is shown in Figure 11 along with the HITRAN generated absorption profile. The laser spectral intensity is indeed asymmetric, and has a FWHM of 0.093 cm\(^{-1}\) (2.8 GHz).

Quantitative analysis of the NO absorption data (cf. Figure 7) would follow a similar path to that outlined above for the N\(_2\)O data of Figure 8, but requires a detailed inclusion of all the relevant, partially resolved absorption lines, which is beyond the scope of the present work. The laser line-broadening effect clearly causes degradation in the measurement sensitivity, as it is defined using the minimum measurable peak absorption, especially for low-temperature and/or low-pressure applications where the absorber lines are narrow. This effect is a thermally-induced characteristic of room temperature, pulsed operation, but can likely be mitigated by design improvements in the thermal coupling of the active region to the heat sink and in the judicious choice of the current pulse characteristics, including pulse width, pulse height, and repetition rate. We are pursuing these design improvements, as well as more rigorous numerical treatments of the line shape convolution analysis.

Our best sensitivity results with the BRD were obtained while monitoring NO on the P5.5 lines. A spectrum of the P5.5 lines for 0.032 Torr NO is presented in Figure 12. The spectrum was
obtained for peak current of 1.02 A, 50 ns pulsewidth, 5 kHz pulse repetition rate, and a TEC temperature of -1 C. The peak absorption is 0.0385. The rms noise on this spectrum yields a SNR of 40, which implies a minimum measurable peak absorbance of $9 \times 10^{-4}$. The corresponding sensitivity for NO is on the order of 520 ppbv-m. We have used the BRD to record peak absorbances as small as $5 \times 10^{-8}$ Hz$^{-1/2}$ under lab conditions and routinely in the range $1 \times 10^{-5}$ under field conditions.$^{18,24}$ It is likely that we did not achieve this same level of performance in this work because of the relatively large background currents present from each detector and the low average photocurrent produced by the laser power. The BRD cannot cancel the uncorrelated noise present on the background photocurrents of the two detectors. We attempted to minimize the background currents by equipping each detector with a cold field-of-view. To further minimize background currents, cold bandpass filters could be used as well. In addition, improvements to the pulse train electronics will allow us to operate with substantially more laser power on the detector. For this initial work, available equipment restricted us to operate only slightly above threshold and with pulse widths of ~70 ns. These conditions severely limited the available laser power. These improvements will allow us to operate well above threshold, in the linear regime, thus producing higher peak power. This, combined with a greater pulse repetition rate, will produce considerably higher average laser power on the detector. For an injection current of 1.02 A, a pulsewidth of 50 ns and a repetition rate of 5 kHz, we estimate the actual average power on the detector was 250 nW. In contrast, the background power on the detector was estimated at 90 nW. With an increase in pulse peak power to 10 mW and an increase in repetition rate to 100 kHz, the average power on the detector will increase to 50 µW. Improvements to the pulse generation electronics
will enable operation with narrower pulsewidths, which will decrease the thermally induced frequency chirp and narrow the laser bandwidth. Improvements to the device packaging (with the epitaxial side mounted downward, in close contact with the TEC, rather than upward as at present) will also improve performance in that operation with higher peak currents and larger repetition rates will be possible without sacrificing linewidth.25 We anticipate that the best overall sensor performance will likely be a compromise between the need for higher laser average power and the need to minimize the laser chirp. We are working to identify the optimal parameters needed to achieve this compromise.

The breadboard apparatus was able to measure a minimum absorbance of $1 \times 10^{-3}$ for a 2 second acquisition using the BRD. With the system improvements mentioned above, we expect the minimum measurable absorption to improve to $1 \times 10^{-5}$. Namjou and coworkers have reported a minimum measurable peak absorption of $5 \times 10^{-5}$ using a pulsed QC laser spectrometer and frequency modulation detection.13 Implementation of these improvements will result in the level of sensitivity necessary to monitor many important trace species with modest pathlengths. For example, a minimum measurable absorption of $1 \times 10^{-5}$ implies a sensitivity for NO of ~35 ppbv-m and for N$_2$O of ~1.5 ppmv-m. Background ambient atmospheric levels of both these species (~100 pptv for NO and ~320 ppbv for N$_2$O) will be measurable with good precision using pathlengths on the order of 10 to 100 m.
4. CONCLUSIONS

We have demonstrated a breadboard laser absorption spectrometer using a room-temperature, quasi-cw mid-infrared quantum cascade laser as a source, in combination with high sensitivity balanced ratiometric detection. We acquired spectra of NO and N$_2$O and have investigated the sensitivity of the QC laser-BRD coupled system. We have demonstrated sensitivities for N$_2$O of 10 ppmv-m and for NO of 520 ppbv-m @ 5.4 µm. From these demonstration experiments, we have identified several system improvements that will increase the sensitivity by an estimated two orders of magnitude. We expect the minimum measurable absorption to improve to 1 x 10$^{-5}$. This implies a sensitivity for NO of ~35 ppbv-m and for N$_2$O of 1.5 ppmv-m. Implementation of these improvements will result in the sensitivity necessary to monitor many important trace species in a variety of environments with modest pathlengths.

5. ACKNOWLEDGMENTS

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6. REFERENCES


Figure Captions

Figure 1. QC laser mount housing.

Figure 2. Schematic of electronics for driving QC lasers in pulsed mode.

Figure 3. General experimental arrangement of laser absorption spectrometer with BRD detection.

Figure 4. (a) Current waveform from the inductive probe and optical waveform from the fast HgCdTe detector; (b) rescaled current waveform overlain on the optical waveform.

Figure 5. N₂O number density determined by the laser spectrometer versus manometer.

Figure 6. Spectrum of the P24E line of the 1₁10 band for 48.4 Torr of N₂O. The spectrum is an average of 100 scans.

Figure 7. NO number density determined by the laser spectrometer versus manometer.

Figure 8. BRD determined N₂O number density versus manometer number density.
Figure 9. Observed and predicted peak fractional absorption at 1859.3 cm$^{-1}$ versus N$_2$O optical depth (data from Figure 8).

Figure 10. Model-corrected laser-determined optical depth versus calculated optical depth for the sample. The line is a least squares fit as described in the text.

Figure 11. Experimental spectrum of Figure 6 compared with HITRAN absorption spectrum and laser spectral intensity.

Figure 12. Spectrum of the P5.5e,f lines of the fundamental band for 0.032 Torr of NO. The spectrum is an average of 200 scans.
Figure 1
Figure 2
Figure 3
Figure 4

(a)

(b)
Figure 7
Figure 8
Figure 10
Figure 12