Five-Channel Infrared Laser Absorption Spectrometer for Combustion Product Monitoring Aboard Manned Spacecraft

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Continuous combustion product monitoring aboard manned spacecraft can prevent chronic exposure to hazardous compounds and also provides early detection of combustion events. As future missions extend beyond low-Earth orbit, analysis of returned environmental samples becomes impractical and safety monitoring should be performed *in situ*. Here, we describe initial designs of a five-channel tunable laser absorption spectrometer to continuously monitor combustion products with the goal of minimal maintenance and calibration over long-duration missions. The instrument incorporates dedicated laser channels to simultaneously target strong mid-infrared absorption lines of CO, HCl, HCN, HF, and CO_2. The availability of low-power-consumption semiconductor lasers operating in the 2 to 5 µm wavelength range affords the flexibility to select absorption lines for each gas with maximum interaction strength and minimal interference from other gases, which enables the design of a compact and mechanically robust spectrometer with low-level sensitivity. In this paper, we focus primarily on absorption line selection based on the availability of low-power single-mode semiconductor laser sources designed specifically for the target wavelength range.

Nomenclature

QC	=	quantum cascade (laser)
IC	=	interband cascade
CW	=	continuous wave
DFB	=	distributed feedback (laser)
TLAS	=	tunable laser absorption spectrometer
MS	=	mass spectrometer
GC	=	gas chromatograph
2f	=	second harmonic (detection)
FPGA	=	field-programmable gate array
DC	=	direct current
TEC	=	thermoelectric cooler
MCT	=	mercury cadmium telluride (detector)
InAs	=	indium arsenide
InGaAs	=	indium gallium arsenide

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CO	=	carbon monoxide
CO_2	=	carbon dioxide
HCl	=	hydrogen chloride (gas)
HCN	=	hydrogen cyanide
HF	=	hydrogen fluoride
H_2O	=	water (vapor)
ppmv	=	part per million by volume

I. Introduction

ACCURATE monitoring of air quality and harmful emissions is an essential component of manned spacecraft safety, and monitoring of specific combustion products is particularly important as an early indicator of equipment malfunctions.[1,2] Existing monitoring systems on the International Space Station (ISS) rely on electrochemical sensors as well as more complex mass spectrometer (MS) and gas chromatograph (GC) technologies. Electrochemical sensors provide portable detection with potentially high sensitivity but require maintenance and calibration, while MS and GC sensors enable extremely high accuracy with a high degree of gas component specificity, but often require substantial infrastructure – including vacuum systems and carrier gases. In contrast, tunable laser absorption spectrometer (TLAS) sensors combine remarkably high accuracy and gas specificity with the potential for portable, continuous, and maintenance-free operation over the course of long-duration missions.[3,4]

In this work, we report on the development of a five-channel TLAS sensor designed to continuously monitor ambient concentrations of CO, HCl, HCN, HF, and CO_2, with low-level detection limits below the standard Spacecraft Maximum Allowable Concentrations for each gas.[5] Monitoring of these potentially hazardous compounds not only enables tracking of general changes in ambient conditions but also allows for detection of fires associated with electrical wiring and electronics packaging. This paper is specifically focused on selection of target laser wavelengths for monitoring each compound. To achieve maximum sensitivity while keeping the instrument compact and robust, our five-channel sensor uses a separate single-mode mid-infrared laser for each gas, with each laser wavelength selected to overlap strong absorption lines and avoid interference from other gases that may be found in manned spacecraft environments. To reach these wavelengths, we have developed distributed-feedback laser sources using various semiconductor technologies, including quantum cascade (QC) instersubband lasers based on InP-matched semiconductor quantum well structures,[6] interband cascade (IC) lasers based on type-II band-to-band transitions in GaSb-matched quantum wells, and Sb-based type-I quantum well diode lasers.[7] Using current tuning to sweep the emission wavelength of each laser across target molecular absorption lines, the TLAS instrument is designed to measure both on- and off-resonance absorption, resulting in a self-calibrating measurement. By targeting strong mid-infrared absorption lines, the instrument is capable of detecting the specified lower limits using a robust two-pass absorption cell configuration with a total optical pathlength of 50 cm. This design approach avoids potential long-term alignment issues associated with more complex multi-pass absorption spectrometers while allowing for unambiguous measurements of specific compounds away from interfering absorption features.

II. Instrument Design

Figure 1 shows a schematic view of the prototype five-channel TLAS instrument, which expands on the design of a previously reported single-channel instrument designed to specifically monitor CO.[8] The five-channel instrument is based on a two-pass open-cell design that can incorporate a safety cover, as needed, but is designed to operate at the same pressure and temperature as the ambient environment. A single heat-sink assembly accepts five sets of dedicated lasers and detectors and sits opposite a mirror bank to create a 50-cm two-pass optical path. Other than the detectors for the two shortest-wavelength channels (as described in the following section), each laser and detector includes an integrated thermoelectric cooler (TEC). Dedicated electronics are used to simultaneously control the temperature of each source and detector, and the ambient temperature and pressure are measured with on-board sensors. The current supplied to the lasers is controlled with dedicated controllers, and the detector response is collected and processed with a custom on-board FPGA board.

Emission from each laser is collimated with an integrated lens before traversing the 50-cm optical path. The TLAS instrument determines the concentration of each target gas by tuning each laser across the selected absorption lines and recording the related detector response. A linearly increasing current ramp is applied to each laser with an additional small-amplitude sinusoidal current modulation with a frequency near 30 kHz, with a slight offset for each channel to avoid crosstalk. Using the FPGA, the detector signal is demodulated at twice the modulation frequency to extract the second-harmonic (2f) response.[9] The quasi-DC response is also recorded after passing the signal through a low-pass filter to eliminate the high-frequency modulation. For relatively low concentrations (typically below 100 ppmv), the amplitude of the 2f response is used to quantitatively determine the concentration of each target gas. At higher concentrations, where Beer's law effects become significant, the integrated area of the DC absorption feature provides a more accurate measure of concentration.

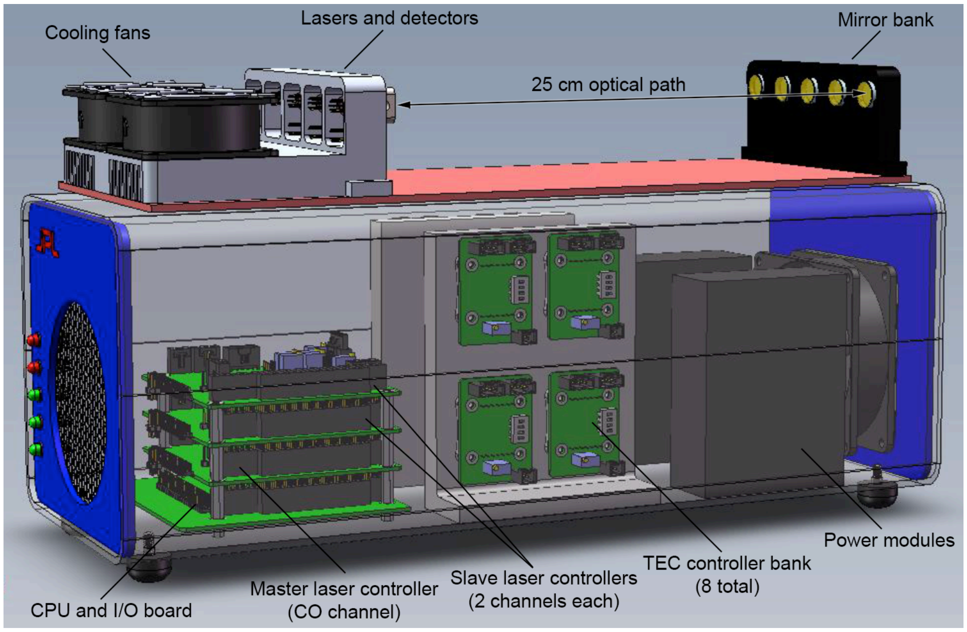


Figure 1. *Layout of the five-channel TLAS instrument, showing the laser/detector bank, the two-pass absorption cell, and the enclosure for control and processing electronics. The design enables simultaneous ambient concentration monitoring with on-board data analysis, including pressure and temperature calibration, to provide real-time quantitative abundance data.*

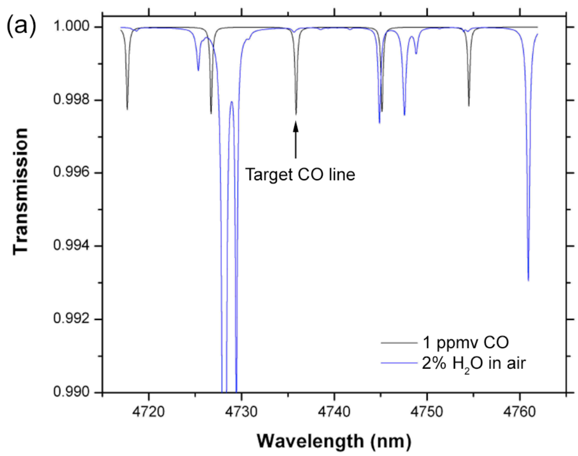
III. Absorption Line Selection

To achieve accurate low-level sensitivity with relatively short optical interaction length and minimal interference from other gases, we have selected the mid-infrared absorption lines indicated in Table 1. Based on the performance of the previously demonstrated single-channel instrument for CO detection, we estimate a resolvable line-center absorption sensitivity of 10^{-4}. To reach the target low-level sensitivities for CO and HCl with an optical pathlength of 50 cm, we have targeted fundamental absorption lines at wavelengths that are difficult to access with conventional type-I interband diode lasers. Consequently, these long-wavelength channels rely on QC and IC laser technology, respectively, while the remaining laser channels use single-mode type-I diode lasers.

Table 1. *Detection range, absorption wavelength, calculated on-resonance absorption (for a 50-cm optical path at standard temperature and pressure), and selected laser technology for each gas targeted by the TLAS instrument.*

Gas	Performance range (ppmv)	Target wavelength (nm)	Relative line-center absorption at lowest detection level	Laser technology
CO	1 – 1000	4735.9	0.0022	Quantum cascade (QC) distributed-feedback (DFB) laser
HCl	0.5 – 50	3572.8	0.0011	Interband cascade (IC) DFB laser
HCN	0.5 – 50	3059.7	0.0004	Laterally coupled (LC) DFB Sb-based diode laser
HF	0.5 – 50	2395.8	0.0027	LC-DFB Sb-based diode laser
CO_2	300 – 30000	2004.0	0.0020	LC-DFB Sb-based diode laser

Figure 2 shows the calculated transmission spectra for a 50-cm optical path at standard ambient conditions in the vicinity of the selected CO and HCl absorption lines. In both cases, water vapor is the primary interfering gas; however, there are spectral windows within which strong fundamental lines of the target compounds are clear of H_2O lines at atmospheric pressure. We note that while the target CO line is well isolated, the HCl feature occurs as a doublet, with the additional line corresponding to the $H^{37}Cl$ isotopologue; however, the lines of the doublet are sufficiently distinguishable to obtain quantitative abundance measurements. The detector for the CO channel is a thermoelectrically cooled MCT photodiode, while the detector for the HCl channel is a cooled InAs photodiode. For both channels, this arrangement results in line-center absorption at least an order of magnitude above the noise floor at the lowest specified concentration of the target gas.



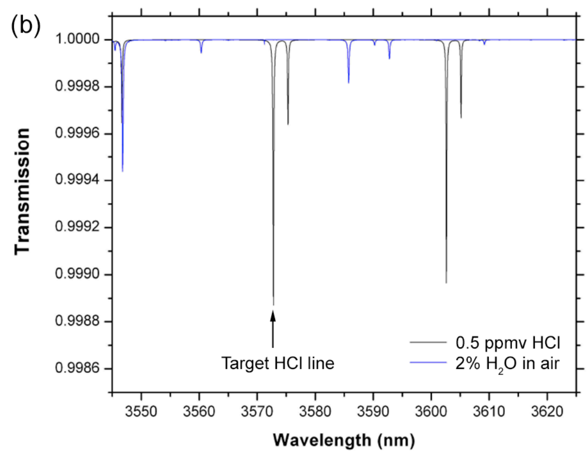


Figure 2. *Calculated transmission spectra for (a) CO and (b) HCl gas at standard temperature and pressure in air over an optical pathlength of 50 cm. Spectra are shown for the target gases at the minimum specified concentrations and compared with the background spectra for a typical ambient environment containing 2% water vapor. The selected absorption lines of the target gases are indicated.*

Due to relatively weak absorption in the mid-infrared, low-level detection of HCN must be performed at wavelengths near 3 µm. Figure 3 shows the selected HCN line near this wavelength, which is relatively free from H_2O interference. The calculated line-center absorption is just four times above the instrument noise floor at the minimum HCN concentration of 0.5 ppmv. The HCN channel uses an additional InAs detector with an integrated TEC, similar to the detector used for the HCl channel.

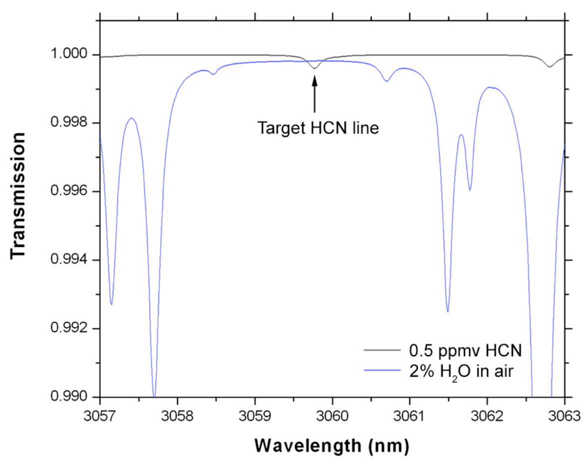


Figure 3. *Calculated transmission spectrum for HCN gas at standard temperature and pressure in air over an optical pathlength of 50 cm. The selected absorption line of HCN targeted by the TLAS instrument is identified.*

The target absorption lines for HF and CO_2 detection are shown in Fig. 4. The selected HF line is free from interference and relatively strong even at the minimum concentration of 0.5 ppmv. Due to the larger lower limit of

300 ppmv for CO_2, this channel is capable of achieving the specified low-level sensitivity by interrogating weaker overtone lines near 2 μm, the strongest of which are relatively free from H_2O interference. Both of these shorter-wavelength channels make use of uncooled extended-wavelength InGaAs detectors.

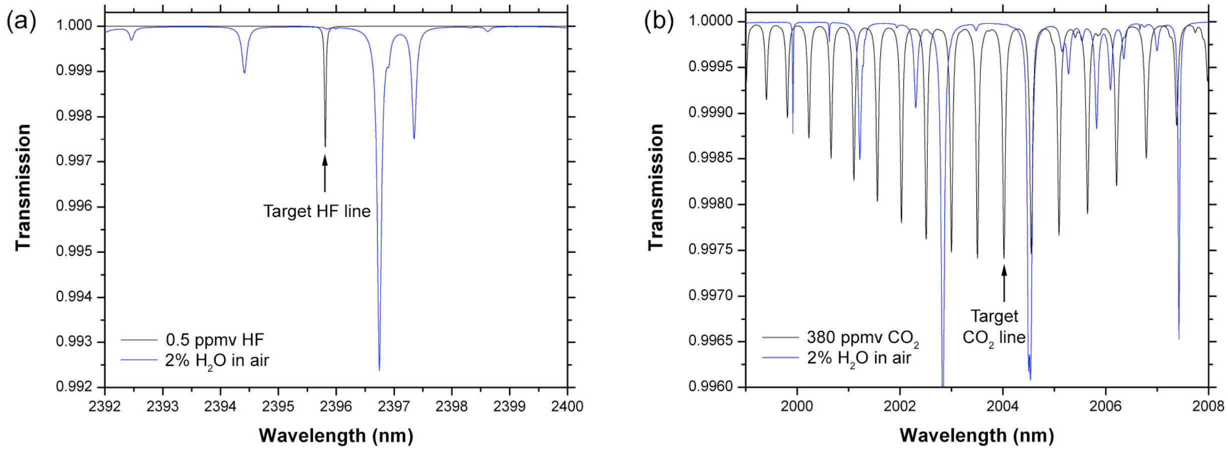


Figure 4. *Calculated transmission spectra and targeted absorption lines of (a) HF gas and (b) CO_2 at standard temperature and pressure in air over an optical pathlength of 50 cm.*

IV. Conclusion

We have described the design of a five-channel laser spectrometer for continuous low-level monitoring of CO, HCl, HCN, HF, and CO_2 aboard manned spacecraft. In particular, we address absorption line selection at mid-infrared wavelengths with a focus on achieving maximum sensitivity with a relatively compact two-pass absorption cell. The completed instrument will enable reliable monitoring of the target compounds for general environmental safety and early detection of fire events.

Acknowledgments

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