Low-power laser-based carbon monoxide sensor for fire and post-fire detection using a compact Herriott multipass cell

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ABSTRACT

With the anticipated retirement of Space Shuttles in the next few years, the re-supplying of short-lifetime sensors on the International Space Station (ISS) will be logistically more difficult. Carbon Monoxide (CO) is a well-known combustion product and its absence in a fire and post-fire environment is a reliable indicator for mission specialists that the air quality is at a safe to breathe level. We report on the development and performance of a prototype compact CO sensor, based on the PHOTONS platform [1], developed for the ISS based on tunable diode laser absorption spectroscopy (TDLAS). A CO absorption line at ~4285 cm^{-1} is targeted using a distributed-feedback (DFB) laser diode operating at room temperature. A custom designed Herriott multipass cell 16cm long, with an effective path length of 3.7 m is employed. Mechanical, optical and electronics systems are integrated into a compact package of dimensions measuring 12.4"x 3.4"x 5". Power consumption is less than 1 W, enabling prolonged battery life. A detection limit of 3 ppm is achieved when performing 40 second long temperature scans. A recent initial test at NASA-JSC was successful. Future improvements include the reduction of the sampling volume, scan time and an improved CO minimum detection limit.

Keywords: carbon monoxide detection, distributed feedback laser, laser absorption spectroscopy

1. INTRODUCTION

Trace gas sensors aboard the International Space Station (ISS) are designated to monitor fire and post fire combustion gas products. These sensors are currently electrochemical analyzers that target such molecular species as: carbon monoxide (CO), carbon dioxide (CO_2), hydrogen chloride (HCl), and cyanide (HCN). However, electrochemical sensors have an orbit service lifetime of about 7 months. With the anticipated retirement of the Space Shuttle program in the next few years, and an estimated 5-year gap between the Space Shuttle's retirement and NASA's next generation space vehicles, missions to the ISS will be carried out by other countries' space programs, thus making sensor re-supply flights less frequent. An alternative to electrochemical sensors are technologies based on tunable diode laser absorption spectroscopy (TDLAS) [2], which can meet the requirements for detection limits, dynamic range, selectivity, response time and a multi-year orbit service time.

The development and performance of such a system, targeting CO, will be reported. CO is toxic to the central nervous and cardiovascular systems. Although CO is not used in spacecraft systems, tests have shown it to be an off-gas product, as well as a by-product of fire in spacecraft events [3]. According to NASA's Spacecraft Maximum Allowable Concentrations (SMAC) values, health concerns begin to occur at CO concentration levels of ~ 15 ppm, where a 30 day exposure will lead to depression and cardiac arrhythmia, and CO levels of ~ 425 ppm with a 1 hour of exposure can cause the same effects. For even higher CO concentrations, exposure to CO becomes fatal.

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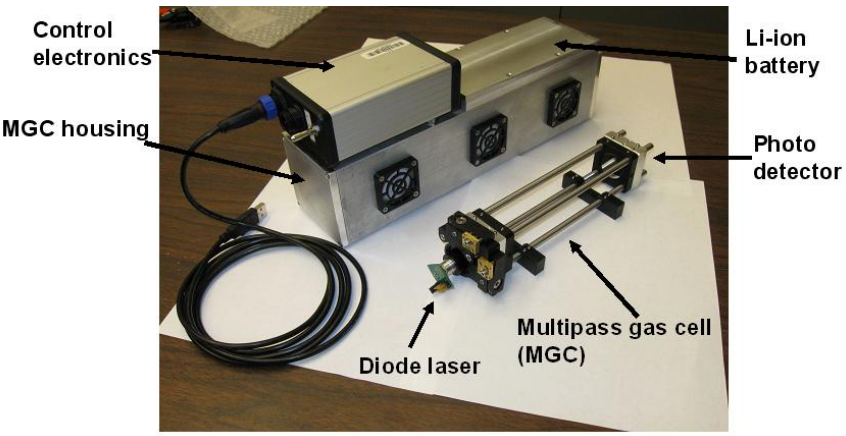

Figure 1. Prototype Herriott multipass TDLAS based sensor for CO detection and monitoring

2. SENSOR PLATFORM

A TDLAS sensor was developed for CO detection based on the Open Access Photonic Networked Sensors (openPHOTONS) platform. See Figure 1. In a simplistic view, a TDLAS system consists of a laser source, the sampled gas medium, and a photodetector. The wavelength of the diode laser is scanned over the characteristic absorption line of the targeted molecular species and the transmitted radiation intensity is measured by a near-infrared photodetector. The absorbance A of the resonant radiation by the targeted medium is described by the Beer-Lambert law, $A = Elc$, where E is the absorption coefficient, l is the path length through the medium, and c is the concentration of the gas. By increasing the optical path length through the sampled gas, the detection sensitivity of the detector can be increased. To maintain a compact sensor size and to increase the optical path length of the radiation, the gas is sampled in a spherical Herriott multipass gas cell.

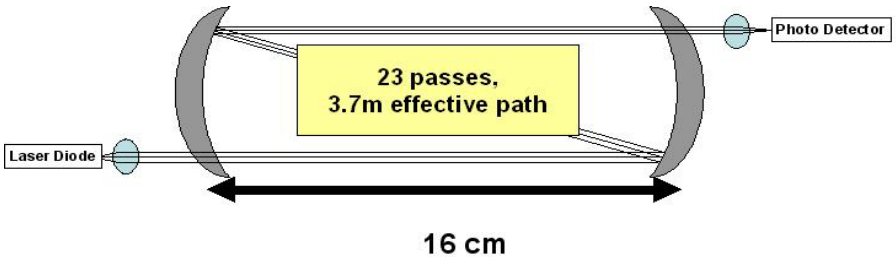

Figure 2. A simplified diagram of a Herriott multipass cell based TDLAS system

A spherical Herriott multipass cell is an optical cavity consisting of two spherical concave mirrors, which effectively bounce the radiation back and forth between two mirrors, thereby increasing the effective optical path length (see Fig. 2). The light enters and exits the optical cavity via strategically placed holes on the mirrors. When properly aligned, the spot pattern can be circular or elliptical. The spots must not overlap with the entrance and exit holes [4]. This factor limits the number of spots on each mirror by the size of each spot and the size of the entrance and exit holes. A narrower beam could achieve a larger number of passes. Using 1" diameter, off-the-shelf mirrors, and a mirror separation of 16.5 cm, a 23 pass configuration is achieved, resulting in an effective optical path length of 3.7 m (see Fig. 3).

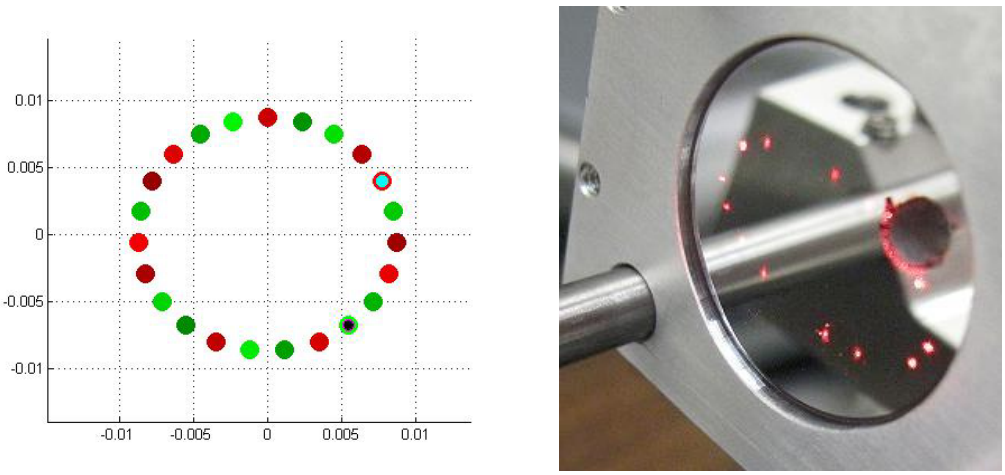

Figure 3. Simulated spot pattern of a 23 pass Herriott cell. Shades of green and red correspond to mirrors 1 and 2, respectively (left). Actual spot pattern of visible HeNe laser on exit mirror. The cell is aligned with a HeNe laser before installing 2.3 µm DFB laser diode (right).

The targeted CO absorption line is located at 4285.01 cm^{-1} (see Fig. 4). The nearby H_2O absorption line at 4282.44 cm^{-1} was used to conveniently and quickly test the CO sensor system.

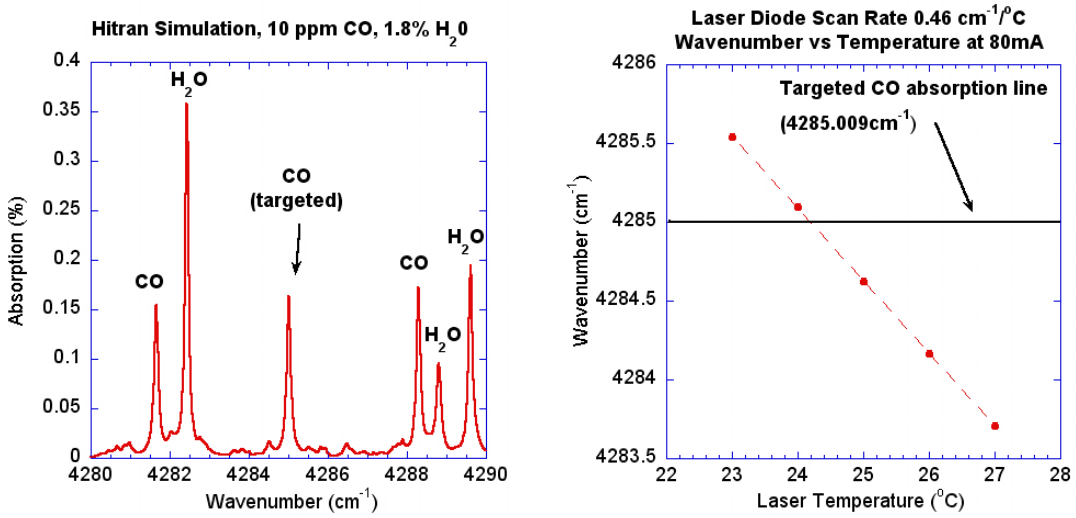

Figure 4. HITRAN simulation of the targeted CO absorption line and neighboring absorption lines (left). Temperature tuning of the LD with respect to the targeted CO absorption line (right).

A 2.3 µm CW, TEC distributed feed-back (DFB) laser diode, mounted in a TO-5 can, is used to access the CO absorption line. Due to the laser diode's highly divergent beam profile, an aspheric lens with a focal length of 4 mm is used to collimate the diverging radiation and direct it into the Herriott multipass cavity. The collimator is coated to minimize etalon fringes. Shorter collimator focal length produces a narrower beam, which in turn can raise the limit of the number of passes in the multipass cell. However, the structure of the TO-5 package of the laser diode limits how close the collimating lens can be placed to the TO-5 can of the laser diode. A custom, compact, adjustable X-Y stage was designed to couple the laser diode to the collimator precisely, and to accommodate for the off-axis mounted location of the laser chip (see Fig. 5). A second, and identical collimator is used to focus the beam exiting the multipass cell onto an un-cooled mercury cadmium telluride (MCT) photovoltaic detector.

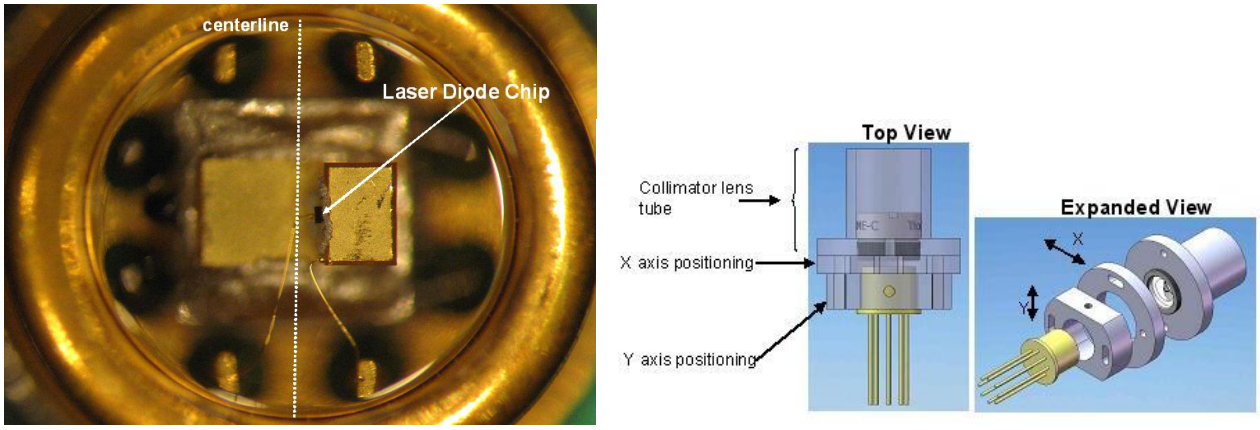

Figure 5. 0.5 mm off-axis laser diode chip (left). X-Y positioning stage for laser diode and collimator (right).

The openPHOTONS platform provides autonomous spectroscopic sensing, including temperature control, wavelength scanning and sinusoidal modulation of the laser diode, sampling the photodetector and 2f harmonic detection using a real-time lock-in amplifier [1]. The openPHOTONS platform uses a two-board configuration. The sensor board provides the functions listed above. The second board, the TelosB module, is a commercially available wireless sensor networking research platform [5]. In this project, the Telos board was used for the purpose of linking the sensor data output to a computer. The two-board sensor system may be powered from a 3.5-6 volt DC power supply. Using a 3.7 volt Li-polymer battery cell, the sensor consumes less than 0.8 watts.

For the low CO ppm concentration levels that need to be monitored in this application, direct absorption spectroscopy is not sufficient. Instead, 2f harmonic detection with a lock-in amplifier is used. This is performed onboard the openPHOTONS platform, and the result is sent to a PC via UART. Additional signal processing is performed in Labview. More specifically, because no reference cell is used, a non-linear curve fit is used to extract a value of the measured CO concentration. Figure 6 shows the raw signal output from the openPHOTONS module, measuring CO from a 49 ppm N_2 calibration gas cylinder.

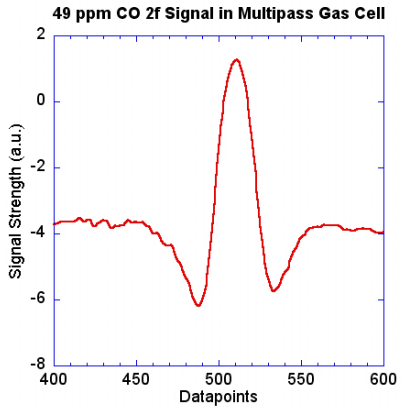

Figure 6. 2f signal output from openPHOTONS sensor board.

3. FIELD TEST RESULTS AND FUTURE WORK

A comprehensive performance valuation of the CO sensor was performed at the NASA-JSC Toxicology Laboratory. A minimum CO detection limit of 3 ppm for a DAQ time of 40 sec was determined. This performance will be improved by improved collimation of the output beam of the laser diode. A collimated, narrower beam will permit an additional 8 passes, for a total of 31 passes, through the multipass cell, thereby increasing the beam path length to 4.6 m, and improving the detection limit by ~27%.

The instrument's dynamic range was tested with incremental concentrations from 10ppm to 2020ppm. It exhibited linear response for the entire range (Figure 7).

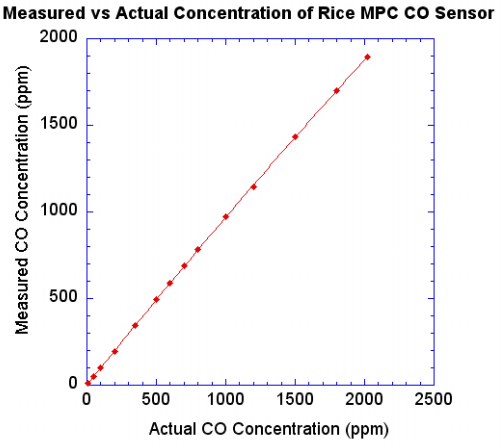

Figure 7. Linearity of sensor's steady state response between 10 ppm and 2020 ppm CO.

Response time is defined as the time it takes for the instrument to reach 80% of the steady state signal concentration. Fast response of a system is important in any gas sensing instrument. The response time of the sensor is dependent on the testing configuration. The first option is to have an open-path multipass cell, where the gas diffuses freely through the sensing path of the optical cavity. The second option is to have the cavity isolated from the outside environment (closed path) and have a directional flow of gas directed through the sensor. This method requires the sampled gas to entirely fill the multipass cavity, thus response time of the sensor is more dependent on the volume of the cavity, as well as the flow rate of the sampled gas.

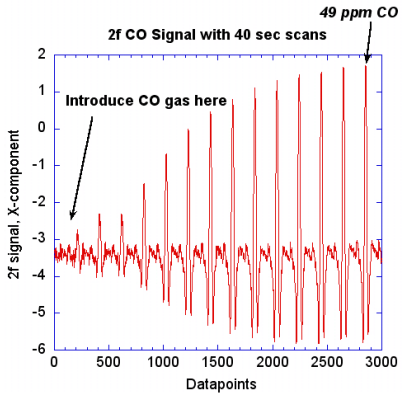

Figure 8. 2f signal output from sensor detecting CO.

Figure 8 depicts the 2f signal of the CO sensor as a function of time in the closed path configuration, at an unspecified flow rate. The performance evaluation demonstrated an 80% response time and 80% recovery time of 2.4 minutes and 2.5 minutes, respectively, in a closed-path configuration, where the volume of the entire sensor enclosure had to be filled with sample gas. In future work, the sampling volume will be reduced by an order of magnitude, from ~ 1L to 0.13L. This will minimize the sampling volume to the optical cavity, and significantly reduce the response time.

In the current sensor configuration, the diode laser is scanned over the absorption line by scanning the temperature of the laser diode. Because of the thermal inertia of the laser package, this puts a limit on the scanning speed of the laser wavelength. Currently, a temperature scan takes ~ 40 sec to complete. An alternative to temperature scanning is to vary the laser diode current. This reduces the scanning time to fractions of a second. This upgrade is being implemented.

The sensor was tested with 0%, 20% and 80% relative humidities, with no effect on performance.

Cross-sensitivity to potentially interfering compounds was tested. When testing for cross-sensitivity, the composition of the sampled gas in the tests was 50ppm CO + x concentration of test gas, where x corresponds to 2000ppm CH_4, 500ppm H_2, 1% CO_2, 30% O_2, 19ppm HCN, 18ppm HCl or 0.25ppm organics. The organic mixture contained acetaldehyde, acetone, acetonitrile, acrolein, acrylonitrile, benzene, butene, cis-dichloroethylene, 1-4 dioxane, ethanol, furan, isopropyl alcohol, methanol, methyl ethyl ketone, methyl isobutyl ketone, proprionaldehyde, tetrachloroethylene, tetrchloromethane, toluene, trichloroethylene, and vinyl chloride. The sensor was found to be cross-sensitive only to CH_4. Elimination of this cross-sensitivity is being addressed with the implementation of a short path-length NH_3 reference cell that will enable linear regression analysis for our curve fitting routine.

4. CONCLUSION

We have applied the openPHOTONS platform to an application which benefits from low power and long lifetime by building a prototype TDLAS sensor to monitor CO levels in a spacecraft environment in case of a combustion related contingency event. WSN capabilities of the platform are available, but were not required for this application. Performance of the instrument is reported. Opportunities for improvements to system performance are identified and upgrades to the instrument are being implemented.

5. REFERENCES

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