

# Advanced Quartz-Enhanced Photoacoustic Trace Gas Sensor for Early Fire Detection

A. A. Kosterev and F. K. Tittel  
Rice University

G. Bearman  
Jet Propulsion Laboratory

Copyright © 2008 SAE International

## ABSTRACT

A spectroscopic trace gas sensor using a distributed feedback diode laser at  $\lambda=1.53\ \mu\text{m}$  and based on quartz enhanced photoacoustic spectroscopy technique is described. The sensor is capable of quasi-simultaneous quantification of trace ammonia, hydrogen cyanide, and acetylene ( $\text{NH}_3$ ,  $\text{HCN}$ , and  $\text{C}_2\text{H}_2$ , respectively) concentrations at  $\sim 100$  ppbv levels with a 4s integration time. The sensor design, responsivity, noise, and cross-talk characteristics are reported.

## INTRODUCTION

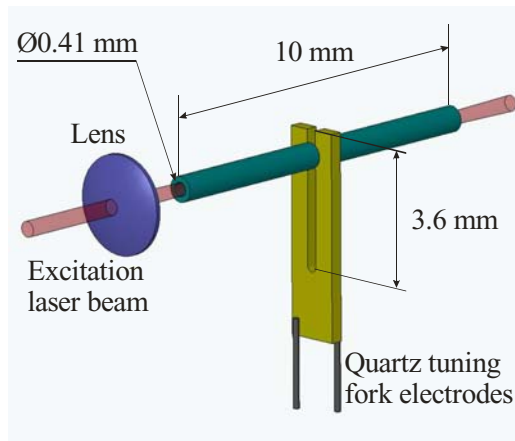
Manned space missions require long term, real-time monitoring of the spacecraft atmosphere to alert the crew of potentially dangerous events such as the onset of a fire, overheating of electric wiring insulation, unintended release of chemicals, or malfunctions of the air regeneration system. Requirements for replacing current trace gas sensors intended for space missions include low mass, small footprint, high reliability, and long operating times. Therefore, there is a need to develop new technologies that can best satisfy these criteria [1]. Laser based chemical gas sensors are emerging devices which have the potential to outperform or complement currently used sensors.[2-5]. Diode lasers in the near-IR (NIR) range initially designed for telecommunication applications are guaranteed for continuous operation for  $>10$  years, feature miniature packaging and low weight. For gas sensing applications these light sources must be supplemented with the appropriate absorption sensing technology. For example J. S. Pilgrim et al. reported such a sensor based on a photoacoustic spectroscopy (PAS) approach [6]. In this paper we describe a multi-species trace gas sensor based on quartz enhanced photoacoustic spectroscopy (QEPAS), a spectroscopic technology using unprecedentedly small and light-weight sensing modules [7-20].

The primary motivation for this work was detection of trace gases that can either signal the fire offset or need to be cleaned up after a fire event. From a list of the relevant molecular species we selected the three molecules which have relatively strong and overlapping but resolved NIR absorption bands and hence can be detected using only one distributed feedback diode laser (DFB DL). The selected species are ammonia, hydrogen cyanide, and acetylene ( $\text{NH}_3$ ,  $\text{HCN}$ , and  $\text{C}_2\text{H}_2$ , respectively). All of these molecules have been previously detected individually using QEPAS technology [3]. The list of accessible species can be expanded by using other or additional laser sources.

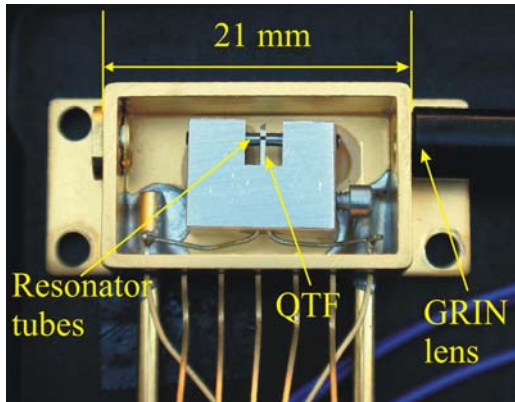
## QEPAS TRACE GAS SENSOR: DESIGN AND PERFORMANCE

**QEPAS TECHNOLOGY** - A novel approach to photoacoustic detection of trace gases utilizing a quartz tuning fork (QTF) as a sharply resonant acoustic transducer was first reported in 2002 [7]. A QTF is a U-shaped, mass produced quartz crystal intended for use in electronic clocks and watches as a frequency standard. QTFs resonate at  $32,768\ (2^{15})$  Hz in clock circuits. A typical design of the QTF based spectrophone (a device detecting optically generated sound waves) and a photograph of its practical implementation are shown in Fig. 1.

**SELECTION OF ANALYTIC LINES** – The commercial availability of high performance diode lasers in the near-infrared (NIR) spectral region has led to their wide use for gas sensing applications. A DFB DL operating at  $\lambda=1.53\ \mu\text{m}$  was used in this work to detect  $\text{NH}_3$ ,  $\text{C}_2\text{H}_2$ , and  $\text{HCN}$ . NIR absorption bands of these molecules overlap and have comparable intensity (see Fig. 2). At the same time, each band consists of narrow individual lines, and it is possible to select lines with minimal or no spectral overlap.



(a)



(b)

**Figure 1:** QTF based spectrophone schematic (a) and its practical implementation (b). The module shown in (b) has two 1/16" tubes to serve as inlet and outlet of gases to be analysed and, when fully assembled, a hermetic top lid. Laser radiation is delivered via a single mode fiber attached to the GRIN lens focusing element.

We searched for specific absorption lines satisfying the following selection criteria:

- Fall within the spectral thermal tuning range of a DFB DL, which is typically  $\sim 15 \text{ cm}^{-1}$  for a  $\Delta T = 40^\circ\text{C}$  laser temperature variation.
- Do not overlap with spectral lines of commonly abundant atmospheric gases such as  $\text{H}_2\text{O}$  and  $\text{CO}_2$ .
- Exhibit minimum cross-molecular overlap.
- Be one of the strongest lines for each target molecule.

Based on these criteria, the absorption lines listed in Table 1 were selected. The sensor operating pressure was chosen to be 450 Torr. This pressure can be obtained using a compact, low power diaphragm vacuum pump, and can be controlled using inexpensive and miniature mechanical components. At the same time, such a relatively high pressure minimizes the  $\text{H}_2\text{O}$  vapor influence on the photoacoustic response of HCN at 32.8 kHz [16]. QEPAS response of the other two

molecules,  $\text{NH}_3$  and  $\text{C}_2\text{H}_2$ , is known to be independent of the gas humidity.

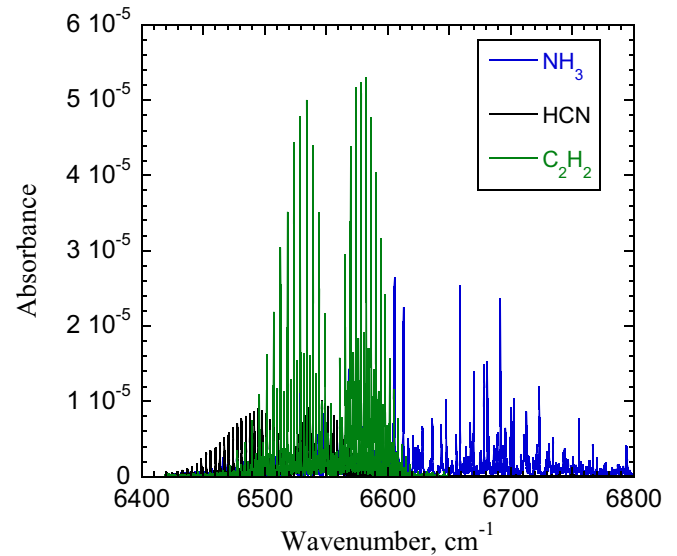


**Figure 2:** NIR absorption spectra of  $\text{NH}_3$ , HCN and  $\text{C}_2\text{H}_2$  obtained from the Pacific Northwest National Laboratory (PNNL) spectral FTIR database (1 atm, 1 ppmv, 1 m, base 10).

Table 1. Selected absorption lines.

| Molecule               | Spectral peak, $\text{cm}^{-1}$ | Laser T, $^\circ\text{C}$ | Laser I, mA | Power, mW |
|------------------------|---------------------------------|---------------------------|-------------|-----------|
| $\text{NH}_3$          | 6528.80                         | +27.0                     | 489         | 62        |
| HCN                    | 6536.48                         | +8.9                      | 456         | 63        |
| $\text{C}_2\text{H}_2$ | 6523.87                         | +39.0                     | 500         | 58        |

**QEPAS SENSOR CONFIGURATION** – A schematic configuration of the multispecies trace gas QEPAS sensor is shown in Fig. 3.

All the elements inside the area outlined by dashed lines are located in a  $250 \times 250 \times 100 \text{ mm}$  metal enclosure with an LCD panel and a keypad. This part of the sensor is called Control Electronics Unit, or CEU. The latest CEU version also contains several optical elements: DFB DL coupled to a single mode fiber, 99/1 and 33/33/33 beam splitters (BS1 and BS2, respectively), and three gas-filled reference cells. Each reference cell has a metal housing incorporating both a fiber coupled collimator and a photodiode. The basic operation of similar single-gas QEPAS sensors was described in earlier publications [13]. The main distinction of the current CEU is a commutator (Comm in Fig. 3) that switches signals from the reference photodiodes, and microcontroller software modifications allowing the laser parameters (temperature, current and modulation frequency) to be set through the 3 set points and channels (Ch0 to Ch2).