A RUGGED LED-BASED SENSOR FOR AIRCRAFT FIRE DETECTION

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ABSTRACT

Current systems **for** fire detection in aircraft cargo compartments tend to have high false alarm rates and have no method for self-testing. Thus, an innovative instrument for enrly aircraft cargo bay fire detection is being developed using inexpensive and rugged mid-Infrared Light Emitting Diodes. This system has the capability to measure multiple gases. including carbon dioxide. which could be used **to** monitor systcin performance. Measurements of signal noise and sensitivity are performed using a prototype instrument. Cas concentration measurements are made using direct absorption and are compared to the results **of** an absorption model. which is also used to examine possible absorbance (interference) **from** ambient water vapor.

INTRODUCTION

Between 1985 and 1991 in the United States more than 32 aircraft accidents and more than 140 deaths resulted from fire and smoke toxicity [1]. These statistics do not include numerous international fire related accidents, such as the 1987 crash of South African Airlines into the Indian Ocean, or more recent events such as the 1995 ValueJet crash in the Florida Everglades. The number and/or severity of these accidents and the number of deaths could have been reduced with adequate fire detection equipment. An ideal instrument for early fire detection would combine high sensitivity, rapid response time. and automatic self-testing, and would have a low false alarm rate. In addition, such a system could provide continuous data to the pilots, giving them the ability to monitor the growth. and possible extinction of a fire (after activation of the on-board suppression system).

Current, aircraft cargo compartment fire detection systems do not meet this ideal. The false alarm rate for these systems is estimated to be at least 90% [2], and possibly as high as 99% [3, 4]. Current gas detection systems also fall short of the ideal system: in recent tests, commercially available CO detectors showed various failures that included false alarms at low CO levels, or worse, no alarms at dangerous CO levels [5]. Thus, Southwest Sciences is developing a novel. low-weight, Light Emitting Diode (LED)-based optical absorption spectroscopy technique for fire detection.

This approach utilizes inexpensive and rugged mid-infrared LEDs to provide high sensitivity, rapid response time, and automatic self-testing with a low false alarm rate. This is to be accomplished by measuring the concentrations of multiple gases to detect incipient combustion. both smoldering and flaming. These gases will include CO, CO_2, and may include HCN and C_2H_2 (acetylene). The mid-infrared (IR) spectral region is to be used instead of the near-IR as the absorbance cross-sections of the target gases are larger, which results in higher detection sensitivities, at least an order of magnitude over the near-IR. The estimated detection limits for this novel technique arc below current OSHA exposure limits for CO and CO_2 [6]. In addition, the sensitivity of this device should allow for detection of CO at or below the current Underwriters Laboratory detection standards for residential detectors (100 ppm).

This instrument could be used for early fire detection in aircraft cargo compartments and other inaccessible locations within an airframe. The commercial applications of the proposed instrument extend to fire safcty in any location requiring fast and accurate detection of a fire,

including, but not limited to, storage warehouses, industrial settings, large office buildings, shopping malls, etc. This technology could also be applied to spacecraft fire safety, providing fire detection for long-duration manned space missions. The same technology used for **fire** detection can be used for air quality monitoring, for a wide range of gases, in almost any setting.

This paper describes the initial experimental effort in developing a prototype of this new sensor, including descriptions of the spectroscopic nature of the target gases, the prototype hardware, and the laboratory results. This paper reports on the results of baseline noise measurements and direct absorbance measurements of CO and CO_2.

MID-INFRARED LED MEASUREMENT OF FIRE GASES

Fire detection with a minimal false alarm rate should be possible by monitoring four key gases: CO, CO_2, HCN, and C_2H_2 (acetylene), which are ubiquitous to many types of fires and can be detected with commercially available LEDs. HCN and acetylene are particularly useful because background concentrations should be negligible for nearly all environments. The scope of the current work is limited to detecting CO and CO_2.

CARBON MONOXIDE

Two-thirds of enclosure fire deaths are attributed to carbon monoxide [7, 8]. Hour-long exposure to CO at concentrations above 200 ppm will cause mild symptoms. At concentrations above 1000 ppm, individuals will lose consciousness within 1 hr. Concentrations above 12,800 ppm are fatal within minutes. Guidelines established by the National Institute for Occupational Safety and Health (NIOSH) limit CO exposure to 40 ppm as an 8-hr time-weighted average [6]. Studies of "enclosure" (room) fires have shown peak CO levels to exceed 100 ppm, and in some cases, exceeding 10,000 ppm [9, 10]. The vibrational bands of CO occur in several spectral regions in the mid-IR where the LEDs can operate. Absorption features in the fundamental band of CO in the 4.54 to 4.65 µm region are well suited for detection of this gas. The cross sections and line positions are tabulated in the HITRAN compilation [11] and plotted in Figure 1.

CARBON DIOXIDE

Although carbon dioxide is a major combustion product, it is not *by **itself*** useful for fire detection because the large atmospheric background concentration (350 ppm) can mask contributions resulting from incipient fires. However, this background level provides a known non-zero background concentration that can be used as a continuous check of instrument operation. The vibrational bands of CO_2 occur in numerous spectral regions in the mid-IR where the LEDs can operate. Fundamental CO_2 absorption features in the 4.20 to 4.34 µm region are useful for detection of this gas given its large background concentration. The cross sections and line positions are tabulated in the HITRAN compilation [11] and also plotted in Figure 1.

SPECTROSCOPIC MODELLING

An understanding of the spectroscopic characteristics of the desired target gases was obtained using the HITRAN database [11]. Modeling focused on determining (1) the effective cross section and absorption of the measurements and (2) possible interference from ambient water vapor.

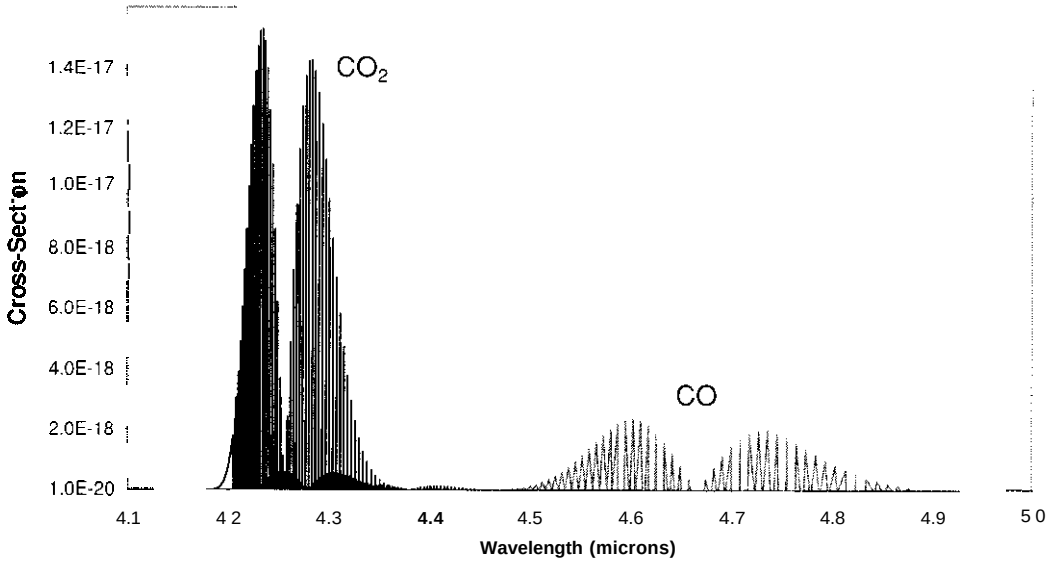

Figure 1. Cross section of CO_2 (4.2-4.4 μm) and CO (4.5-4.9 μm) in the mid-IR (P = 1 Atm, T = 298 K).

EFFECTIVE CROSS SECTION AND ABSORPTION

This technique utilizes a broad emission, covering a large portion of an absorption band. instead of a single line feature that would be used for a high-resolution tuned diode-laser. The HITRAN database provides data on individual lines, not entire absorption bands, such as those shown for CO and CO_2 in Figure 1. Thus, an effective cross section and an effective absorption coefficient arc required. The absorption coefficient (a) is a function of the attenuation of an incident light beam through an absorbing medium, as defined by Beer's Law:

$$a = \ln (I_O / I) \qquad (1)$$

in which I_O is light intensity incident on the gas sample, and I is the transmitted intensity. The effective cross section and effective absorption are related through the Beer-Lambert Law:

$$\alpha_{EFF} = \sigma_{EFF}\, N\, L \qquad (2)$$

in which (L) is defined as the path length through the absorption cell, and (N) is the number density. The effective cross section (σ_{EFF}). is defined as the sum of the line strength in the filter bandwidth averaged over the filter bandwidth:

$$\sigma_{EFF} = \Sigma\, S(T) / \Delta\nu_{FILTER} \qquad (3)$$

The line strength, S(T), is a measure of how strongly light is absorbed and is a function of Temperature (T). Thus, an effective absorption coefficient (α_{EFF}) can he computed by using the line strengths acquired from HITRAN for the desired filter bandwidth.

INTERFERENCE BY WATER VAPOR

A major concern while performing spectroscopic measurements is interference from ambient species. In this case, water vapor is present in the ambient air and could potentially interfere with the fire gas measurements because it has absorption peaks in the same wavelength region as CO. A parametric study was performed using the HITRAN database using the methods described in the previous section to determine the absorbances of water vapor and CO in the range of 4.53–4.77 μm. (This is the bandwidth of the CO filter used in the prototype instrument.) This study compared water vapor (4000 to 40,000 ppm) and CO (100 ppm) concentrations for temperatures ranging from 283–310 K and pressures from 0.7 to 1 Atm. The temperature and pressure range represent potential conditions within an aircraft cargo compartment. In almost all of the cases, the computed absorbance for CO was at least an order of magnitude larger than for H_2O (Table 1).

TABLE 1. COMPARISON OF WATER VAPOR AND CARBON MONOXIDE ABSORBANCES.

T (K)	P (Atm)	*CO* 100 ppm	H_2O 40,000 ppm	H_2O 10,000ppm	H_2O 4000 ppm
310	1	1.88E-02	2.10E-03	5.02E-04	2.10E-04
298	1	1.97E-02	1.64E-03	4.10E-04	1.64E-04
283	0.7	1.44E-02	9.40E-04	2.35E-04	9.40E-05

EXPERIMENTAL HARDWARE

As the approach for this gas detection system is optical spectroscopy, a light source and a detector are required, as are control electronics for both devices. The prototype system described in this section (patent pending) is being built with off-the-shelf components.

MID-IR LEDS & DETECTORS

Light Emitting Diodes (LED) that operate at mid-infrared (IR) wavelengths have recently become available. Peak wavelengths, tailored to user specifications, span from 2 to –4.6 pm. The output spectral linewidth at full-width, half-maximum (fwhm) ranges from 150 to 600 nm and the continuous wave (cw) output power from 300 to 20 μW, at the shortest to longest wavelengths, respectively. They are inexpensive ($350 each, $145 in large quantity), rugged (>100,000-hr lifetime, cw or pulsed), and compact (–5 mm dia.) in size. The nominal operating temperature for these devices is -10 to 40 "C. The LED output can be collimated with a micro parabolic reflector behind the emitter, which increases the LED diameter to 10 mm. To monitor CO and CO_2 the LED emission linewidth must be narrowed with appropriate mid-infrared band pass filters: baseline (3.91–4.09 pm), CO_2 (4.16–4.45 μm), and CO (4.53–4.77 pm). Mid-IR LED signals *are* measured either with a thermoelectrically cooled mercury cadmium telluride (HgCdTe) infrared detector, or a liquid nitrogen cooled indium antimonide detector. Both detectors have good spectral response out to 5 μm and compact size (1.0 mm diameter active area). The HgCdTe detector is rugged, and well suited for continuous monitoring applications.

PROTOTYPE DETECTION SYSTEM

A schematic of the gas detection system (patent pending) is shown in Figure 2. This system uses two LEDs pulsed at 10 kHz with a 50% duty cycle. A pulse generator sends timing signals to a pair of current controllers, which in turn, power the LEDs. The light from the LEDs is filtered to a specific wavelength region, combined using it cadmium telluride (CdTe) window, and then focused onto the detector using two spherical plano-convex calcium fluoride lenses. The light passes through an absorption cell that has a path length of 35.5 cm before reaching the detector.

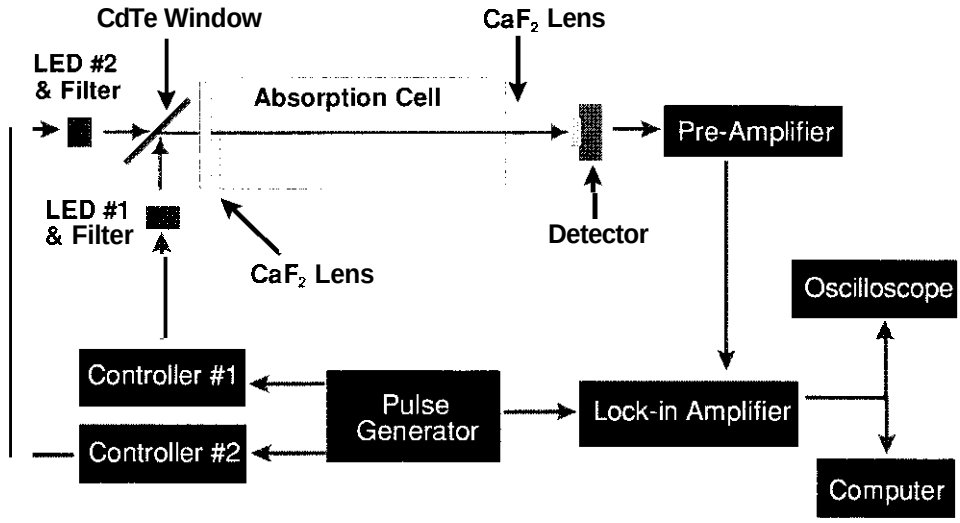

Figure 2. Schematic of the laboratory prototype fire sensor (patent pending).

The output signal from the detector is sent to a pre-amplifier and then to a lock-in amplifier that provides phase-sensitive detection at the LED modulation frequency. The output from the lock-in can be directly view on an oscilloscope, or captured using an analog-to-digital data acquisition board in a PC. The laboratory prototype for this system is shown in Figure 3.

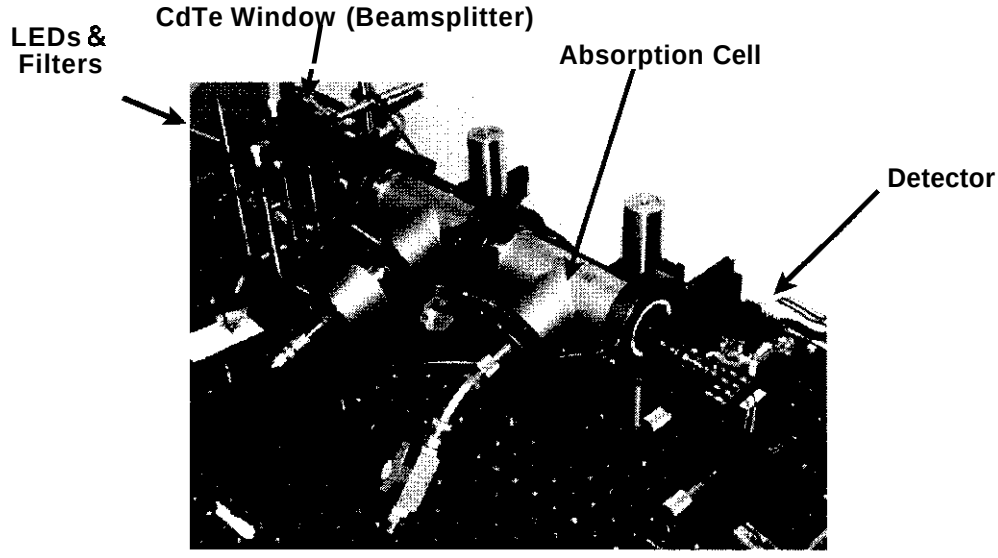

Figure 3. Prototype fire sensor.

EXPERIMENTAL RESULTS

The experiment program consists of three stages. In the first segment, baseline data and signal noise measurements were made. In the second segment, direct absorption measurements of CO_2 and CO were performed using a single LED. In the final set of experiments, yet to be performed, two LEDs will be used for differential absorption measurements.

BASELINE MEASUREMENTS

Experiments were performed to determine the baseline signal and noise for each LED and filter using the indium antimonide detector. The LEDs were aligned such that the lock-in amplifier signal output was 6000 millivolts for each LED. The noise level was measured by offsetting the data signal to **zero** and measuring the **RMS** of the remaining signal using an analog-to-digital data acquisition board in a PC. The noise levels were ~1 millivolts, which yielded a signal to noise ratio of 6000:1. Using this noise value as the minimum detectable signal, and using the absorption model to compute the effective absorption, the minimum detectable concentrations for CO and CO_2 were 1 ppm-meter and 2 ppm-meter respectively.

DIRECT ABSORPTION MEASUREMENTS

In these experiments, measurements were taken using a single LED, with and without an absorbing gas in the cell. For carbon dioxide, measurements are made with the cell evacuated (0 ppm CO_2), and filled with air (~ 350 ppm CO_2 at 600 Torr). The ratio of the measured light intensities (I_{AIR}/I_{VACUUM}) is 0.8418, which corresponds to an absorbance of 0.172. The measured absorbance is within 10% of the effective absorbance (0.155) computed using the **HITRAN** database. The experimental absorption cross-section is 7.1×10^{-19}, in comparison to the effective cross section of 6.4×10^{-19} computed using the **HITRAN** data in **Eq.** *(2)* and (3).

For carbon monoxide, measurements are made with the cell filled with air (0 ppm CO), and filled with CO at 2 Torr. The ratio of the measured light intensities (I_{CO}/I_{AIR}) is 0.9887, which corresponds to an absorbance of 0.0113. The measured absorbance is within 30% of the effective absorbance (0.0087) computed using the **HITRAN** database.

FUTURE WORK — DIFFERENTIAL ABSORPTION MEASUREMENTS

The goal of this technique is to discern small concentration changes, potentially as small as the limit set by the baseline noise measurements. This technique (patent pending) uses two LEDs and examines the differential measurement from the signals. The LED emission is filtered to provide a reference signal, and an absorption signal. Initially, the LED input currents are adjusted such that the detection signal level (I_O) is the same for each LED/filter combination with no absorbing gas present in the cell (Figure 4). When there is an absorbing gas, such as CO or CO_2 present in the cell, one of the detected intensities decreases (Figure 4).

When the phase sensitive amplifier processes these signals, the resulting output for the case without an absorbing gas is zero. (The LEDs are modulated 180 deg out of phase). When an absorbing gas is present, the signal from the second LED drops below I_O, and the lock-in signal increases. This change in signal is proportional to the gas concentration.

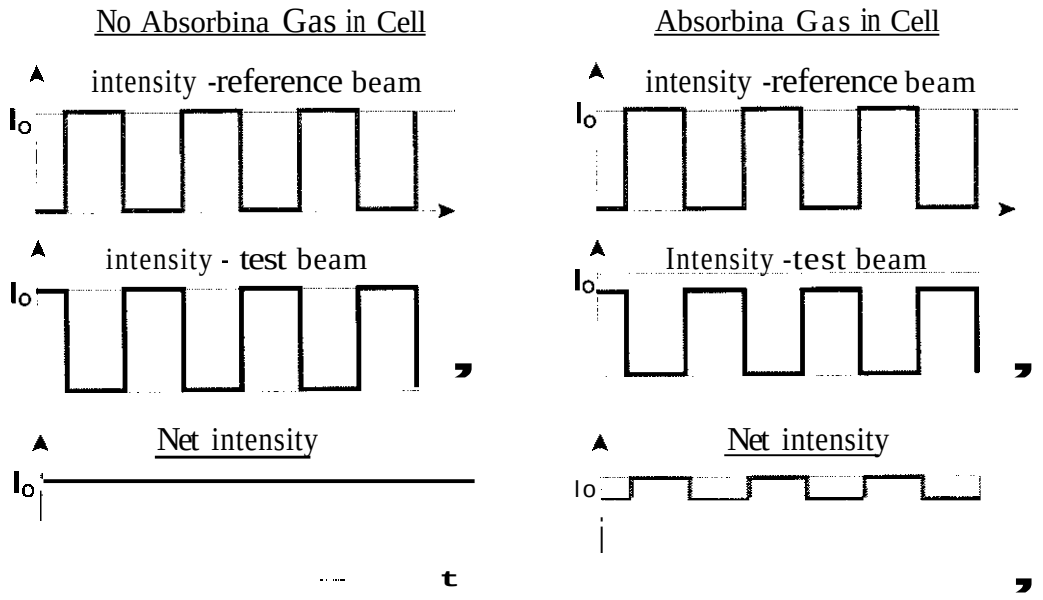

Figure 4. Differential absorption measurements (patent pending).

CONCLUSIONS

A new, innovative technique (patent pending) has been utilized for measuring trace gas concentration. The mid-IR LEDs used in this system are ideally suited for continuous monitoring in situations that require a small, low-cost alternative to conventional systems, such as in aircraft cargo compartments. Using multiple LEDs, the system has the ability to measure separately the instantaneous concentration of multiple gases, greatly reducing the likelihood of false alarms, and increasing the likelihood for detecting incipient fires. In addition, continuous monitoring of CO_2, which has a non-zero ambient concentration, can be used for real-time testing of instrument performance.

The next step in the development process for this detector is to prepare a fully functional "engineering model" that can be tested in more realistic environments. This may include testing at NIST, or a university based fire-sciences lab. Additionally, this instrument could be integrated into a sophisticated aircraft control system, such as the system prototyped by Boeing [12].

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