Wireless infrared gas sensor

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Abstract: Infrared hydrocarbon gas detectors are essential for safety, but the requirement for cabled power complicates installation. A new low-power optical design based on a micro-opto-electromechanical system gives several years of reliable battery operation.

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1. Introduction

Reliable and fast detection of hydrocarbon gas leaks is important for safety in the petroleum industry. Infrared absorption measurements is a widely used and approved method. *Point detectors* are installed at strategic locations and measure the gas concentration of the air flowing naturally into the detector's measurement volume. The measurement itself is not particularly challenging from a spectroscopist's point of view, since explosive mixtures of hydrocarbons in air typically absorbs more than 10% of the power in a wide spectral band using a pathlength of only 10 cm. However, the real challenge lies in designing a reliable, practical, and not too expensive instrument also satisfying the following requirement: *No recalibration shall be necessery during a lifetime of up to 20 years, in a wide operating temperature range and harsh environments.*

There are also strict requirements on the probabilities for false negatives (non-detection) and false positives (false alarms). Several commercially available gas detectors have demonstrated that they satisfy the requirements above. However, the energy consumption may be in the range 1 W to 5 W, mainly because of the modulated infrared sources, and as much as 80% of the detection system cost may come from installing cables for power supply. Therefore there is a demand for battery operated, wireless detectors.

2. Energy-efficient sensor system

We have implemented several techniques for reducing energy consumption from watts to milliwatts, and three of the most important are:

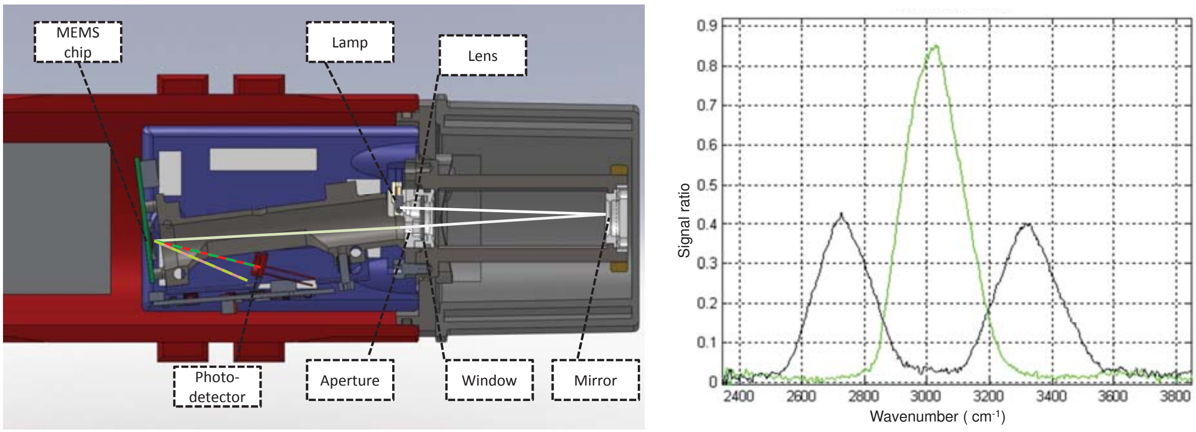
1. The infrared sensor is only used when needed, and spends much of its time in a sleep state
2. The wake-up time is short, and a complete measurement takes less than one second
3. A compact and simple optical design makes efficient use of the light from a small source.

To wake the infrared sensor from sleep state, there is an additional monitoring sensor that uses ultrasonic pulses to measure the speed of sound in the measurement volume. Any significant change in the air composition will be detected as a change in the pulse propagation time, which initiates an infrared measurement [1].

For this to work, the infrared sensor must be able to wake on demand and produce reliable output within one second, before it goes to sleep again. It must also be energy-efficient. We found that such a sensor could be made based on a voltage-controlled holographic MEMS chip [2] that can switch between measurement and reference wavelength bands.

3. Infrared sensor design

Figure 1a) shows a drawing of the infrared sensor. The radiation source is a small incandescent lamp. A miniature silicon lens and a concave mirror image the filament onto a 2.5 mm wide aperture that is the entrance aperture of



(a) (b)

Fig. 1. The MEMS-based infrared gas sensor. (a) Optomechanical design showing the main optical components, the beam of broad band light (white line), and the filtered and modulated beam (red and green dashed line). The battery compartment is partially shown on the left. (b) The filter functions used for methane detection, corresponding to the two states of the MEMS (green and black), measured using an external interferometer.

the spectrometer. There is a sapphire window separating the internal parts (illumination and spectrometer) from the external part (measurement volume and mirror). The measurement path length is 135 mm.

The core of the spectrometer system is a micro-electromechanical system (MEMS) that disperses, focuses, and modulates the incident light. The entrance aperture is imaged by a curved micromechanical diffraction grating onto the photodetector plane as a dispersed spectrum. The 1 mm square PbSe photodetector is positioned to detect the correct wavelength band. By applying a control voltage to the MEMS chip, the diffracted light can be redistributed between the diffraction orders, so that we can define a gas state and a reference state shown in Figure 1b) as green and black curves respectively. The same light source and detector are used for the gas and reference measurements.

3.1. *Measurement algorithm*

After waking up and stabilizing the amplifier, the detector voltage is sampled for 100 ms. Then the lamp is powered up and stabilized, which takes approximately 200 ms. During the next 100 ms, the voltage controlled filter switches between the measurement state (central absorption band) and the reference state (double sideband) at a frequency of 1 kHz. The filter shapes are designed to give approximately equal power in the two states when there is no gas present, and the difference signal can be measured with greater accuracy than the signal levels corresponding to each filter state separately. The complete measurement takes 0.5 s, and is completely self-contained, with no additional filtering.

3.2. *Comparison with non-dispersive infrared gas detectors*

Unlike a laboratory spectrophotometer that can be manually recalibrated as a part of the measurement procedure by subtracting the dark signal and normalizing the response of the photodetector(s), an infrared gas sensor must rely on built-in mechanisms to compensate for drifting source intensities, detector response, and various other error sources. The simplest non-dispersive infrared (NDIR) gas sensors have only one wavelength channel and are considered unreliable for safety applications. More advanced detectors use a combination of reference wavelengths and/or reference lightpaths to achive self-calibration.

A typical configuration of a *doubly compensated* detector uses four measurements to calculate gas concentration (two wavelengths combined with two detectors measuring internal and external light paths). Ideally this method eliminates error sources such as drifting source intensities or dirty optical windows.

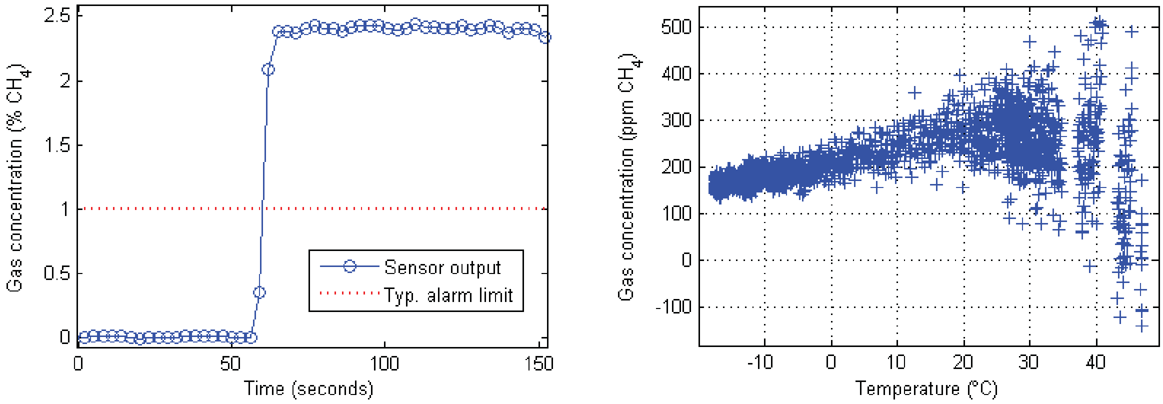
When concerned about energy consumption, there are some disadvantages with the doubly compensated system as described: Rapid infrared source modulation is required, and energy is lost in the heating and cooling cycle. There is an arrangement of beam splitters that results in lost light. In order to achieve stable measurements there must be a certain degree of thermal equilibrium in the system. This often requires a start-up times from tens of seconds up to several minutes, and excludes intermittent operation with short duty cycles.

4. Results

The energy consumed during a single gas concentration measurement as described in Section 3.1 has been measured to 140 mJ. Approximately two thirds is required by the light source, and one third by the microcontroller and electronics circuitry. If triggered every minute, the average power becomes 2.33 mW, and this allows several years of operation on a lithium-thionyl chloride battery pack with a volume less than 250 cm^3.

Because a complete measurement takes less than half a second, the response time is dominated by the measuring frequency and the flow of gas into the measuring volume. An example gas measurement is shown in Figure 2a).

The repeatability depends on temperature, as can be seen from the typical thermal cycling measurements shown in Figure 2b). When the sensor is calibrated for methane, the typical zero point repeatability varies from a standard deviation of 10 ppm at −20 °C to 100 ppm at 45 °C. After the initial calibration, thermal cycling and ageing may result in offset errors. In the example, the error ranges from 150 ppm to 300 ppm, which is well below required limits. Further tests are required to determine sensor accuracy and stability over several years.



(a) (b)

Fig. 2. Measurements. (a) Gas concentration measured every 3 seconds. A test mixture of 2.5% methane in air is added after approximately one minute. (b) Zero point stability measurements during part of a temperature cycling.

5. Conclusion

We have demonstrated a new battery powered gas sensor that is capable of providing reliable detection of hydrocarbon gases over a wide temperature range, with several years battery lifetime and no re-calibration.

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