Self Powered Non-Dispersive Infra-Red CO₂ Gas Sensor

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Abstract. This paper describes a non-dispersive infra-red CO₂ gas sensor, incorporating a mid-infra-red solid state light source/detector combination, tuned to match the spectral absorption characteristic of CO₂ gas. Injection moulded optics provide low cost manufacture. Continuous operation power consumption is < 3.5mW and pulsed mode with energy per measurement < 6mJ. Self powered operation using a solar cell is demonstrated together with wireless capability. Performance of two path length variants (20mm and 70mm) is described. The sensor shows invariant temperature output characteristic from -25 to 50ºC. Accuracy level is typically ±3% of reading.

1. Introduction

Information concerning carbon dioxide (CO₂) concentration levels is an essential element in air quality monitoring and control. CO₂ is an insidious gas, therefore changes in concentration are difficult for humans to recognize. The gas is safe in low concentrations (typically <1000ppm), however prolonged exposure at moderate levels (>5000ppm) can lead to a range of health related problems such as sick building syndrome [1,2] causing fatigue like symptoms. Current and incoming legislation requires CO₂ gas monitoring within building environments for optimal control of air quality [3,4]. Moreover, such CO₂ gas monitoring is employed within demand control ventilation systems used for building heating ventilation and air conditioning as a means of reducing energy consumption in addition to control of indoor air quality control. In industrial environments where process generated CO₂ dominates, for example in breweries, soft drinks, packaging industry, freezer storage etc, the maximum permitted CO₂ concentration according to most standards can be as high as 5,000 ppm during an 8-hour working period. CO2 gas monitoring in this case is required to ensure compliance with industrial health and safety requirements. Such levels are normally not found in home or office environments where people are the main source of carbon dioxide. Current and emerging building indoor air quality and industrial safety markets are require real-time continuous monitoring of CO2 concentration levels, creating high volume demand for low cost, low power consumption CO2 gas sensors, driven in many instances by legislative requirements. Increasing requirements for wireless networked CO2 sensors is placing emphasis on low power consumption, at levels enabling battery operation and ultimately power scavenging/ self powering technologies.
Currently there are two types of gas sensors commonly available for monitoring CO\textsubscript{2} concentrations in air, i.e., non-dispersive infrared (NDIR) and solid electrolyte sensor types. NDIR sensors have performance advantages in terms of long-term stability, accuracy, and power consumption for CO\textsubscript{2} measurement. Hence, NDIR sensors are the most widely used for the real-time measurement of carbon dioxide. Solid electrolyte types have cost advantages, but the product performance is not good enough to allow their use in any but the least demanding applications.

The NDIR method is an optical method of detecting gases. This relies on the fact that many gases absorb specific wavelengths of infra-red light. It is possible to calculate the gas concentration, by passing light through a defined length and measuring how much light is absorbed at the specific wavelength absorbed by the gas. For CO\textsubscript{2}, the commonly used wavelength is 4.26\textmu m, a wavelength which is strongly absorbed by CO\textsubscript{2}, but not absorbed at all by other commonly found gases or by water vapour.

Current NDIR CO\textsubscript{2} gas sensor utilise an incandescent bulb and pyroelectric light source/ detector combination, with consequent high power consumption – typically 50 to 200mW. This necessitates hard wired installation or short battery life, which is costly and at odds with legislatively driven requirements for multiple wireless capable sensor install in buildings, transport systems and also the need for portable sensors for use in safety and industrial applications.

Moreover, incandescent light sources have additional restrictions for use in applications requiring low power consumption, such as extended stabilisation time (typically > 10 minutes) and limited ability to pulse (typically < 4Hz) for short duration measurement. In addition, output wavelength drift with bulb lifetime necessitates use of complex referencing optics and optical filtering.

In this paper a low power consumption NDIR CO\textsubscript{2} gas sensor based on mid-infrared solid state light emitting diode (LED) and photodiode (PD) is described. LED’s offer the advantage of high source emittance, fast modulation rates, room temperature operation with no burn-in and are more cost effective than laser diodes for deployment in practical gas sensors [5]. Specific performance benefits are described including low power consumption (<3.5mW), rapid stabilisation time (<2s) and ability to pulse for short duration measurements. Moreover, intrinsic wavelength stability of the solid state LED/ PD combination allows use of simplified and low cost injection moulded reflective optics with no requirement for active alignment for sensor assembly.

2. Sensor Configuration

The NDIR sensor described in this paper comprises a narrow bandgap III-V LED light source and photodiode detector. Mid infrared radiation is launched into an optical structure which defines lightpath and chamber into which gas diffuses, causing a reduction in light transmission at the sensing wavelength. Electronics and intrinsic firmware control LED/ PD drive current/voltage, pulsing and signal processing. Output parameter is CO\textsubscript{2} gas concentration, stabilised over the sensor operating temperature range. Sensitivity is determined by optical pathlength.

Sensor constituent parts and assembly are described as follows.

2.1. LED/ PD Combination

Photonics technology has been used [6], producing LED sources and PD detectors operating at mid-infrared wavelengths of interest in gas detection. The technology is based on a pentanary AlGaInAsSb narrow bandgap III-V material combination [7,8].
Spectral characteristics of both LED and PD can be tuned by altering the ratio of the III-V material stoichiometry [8].

Figure 1a illustrates LED and PD configuration. Figure 1b shows actual LED and PD mounted on an electronic bridgeboard ready for assembly onto the optical and electronic chassis.

This technology produces LED and PD’s which are tuned to a relatively narrow bandwidth. Used as a pair the bandwidth of the combined system is narrower still. This narrow bandwidth allows the LED and PD to be used without additional optical filtering, further reducing cost and simplifying the optical design.

LED and PD detector operating voltages are reduced to 2.5V by enhanced impedance matching of the LEDs and PD through segmentation of the LED and PD active areas [9]. Operating voltage at 2.5V is well suited to interface with 5V and 3.3V electronics.

2.2. Performance Modelling, Optics and Signal Processing

Detailed optical modelling of sensor sensitivity and noise has been carried out to identify necessary optical pathlength for CO₂ gas sensor, covering required concentration ranges, accuracies and data processing.

Figure 2 illustrates modelled and measured noise (expressed as percentage of actual CO₂ concentration) for two pathlengths (20 and 70mm). Modelling indicates no one pathlength can provide high accuracy (<±5% of reading) over full range from 200ppm to 100% concentration. The model utilises complete absorption spectrum for CO₂.
Figure 2 Modelled sensor noise (expressed as a percentage of actual CO2 concentration level) for two pathlengths: 20 and 70mm. Measured noise for the two sensor pathlengths is shown.

A minimum of two pathlengths is required to provide accuracy $\leq 5\%$ of reading. 20mm pathlength is suited to concentration levels from 5 to 100% whilst 70mm pathlength provides complementary required accuracy from 200ppm to 5%. Figure 3 shows the optical/electronic assemblies for the 20 and 70mm pathlength sensors, both incorporating low cost, injection moulded reflective optics.

Figure 3  Assembled (a) wide range (actual size 20mm diameter, 25mm length including electronics) and (b) ambient sensors (note ambient is shown without protective cover. Size with cover 42mm diameter, 15mm thickness including electronics)

Assembly requires no active alignment of LED/PD bridgeboard and optics.
Both sensor configurations can be calibrated from zero to customer specified maximum range. However, wide range is normally supplied in four standard ranges: 0 to 5%, 0 to 20%, 0 to 65% and 0 to 100% whilst ambient is supplied in three standard ranges 0 to 5000ppm, 0 to 1% and 0 to 2%.

Figure 4 shows the signal processing scheme. The Micro Controller Unit (MCU) periodically sends a very fast pulse train to the Infra Red LED (IR LED) via a GAIN stage. The modulated IR light pulses fall on the Photo Diode detector.

![Signal processing configuration](image)

IR light level is detected by the PD and is amplified by a GAIN stage before being captured by the MCU’s Analogue to Digital Convertor (ADC) thus making a digital version available for processing. The digital version of the IR light level is processed by the MCU which then provides a serial data output indicating the \( \text{CO}_2 \) concentration present between the mid-infrared LED and the PD.

3. Performance

Performance of the two pathlength configurations is provided in Table 1.

| Parameter                              | Wide range 20mm pathlength | Ambient 70mm pathlength |
|----------------------------------------|-----------------------------|-------------------------|
| Power (continuous)                     | <3.5mW                      |                         |
| Energy per measurement (pulsed)        | 6mJ                         |                         |
| Power up stabilisation time            | <2s                         |                         |
| Peak current                           | 33mA                        |                         |
| Average current                        | 1.1mA                       |                         |
| Input voltage                          | 3.3V                        |                         |
| Accuracy                               | ±3% (of reading)            |                         |
| Standard ranges                        | 0 to 5, 20, 65 and 100%     | 0 to 2000ppm, 1 and 2%  |
| \( T_{90} \)                            | 4 secs                      | 30 secs                 |
| Operating temperature range (°C)       | Standard: 0 to 50 °C; extended -25 °C to +50 °C |                         |
| Storage temperature (°C)               | -30 to +70 °C               |                         |
| Relative humidity                      | 0 to 95% RH non-condensing  |                         |
| Dimensions                             | 20mm x 25mm                 | 43mm x 15mm             |

Table 1 Performance parameters for wide range (20mm) and ambient (70mm) sensors
Figure 5(a) shows temperature invariant performance over six temperatures (-25, 0, 15, 25, 35,55°C):

![Figure 5(a) Temperature stability at 500ppm, 1000ppm, 2000ppm, 5000ppm, 1%,2%,5% ove six temperatures and (b) battery life (three AAA batteries) as a function of measurements per hour](image)

Figure 5(b) shows battery life (three AAA batteries) as a function of number of readings per hour, indicating battery life is between five to ten years for typical sampling rates used in building control and industrial safety applications.

Self powered operation with wireless data transmission has also been demonstrated with a 67 x 28mm silicon solar cell with 200lux light level [10]. Self powered operation enables sensor to operate at one reading every 10 minutes.

4. Summary and Conclusions

A novel NDIR CO\(_2\) sensor is demonstrated with less than 3.5mW power consumption in continuous operation and 6mJ/ measurement in pulsed mode. Energy consumption levels in pulsed mode enable self powered operation and wireless data communication using a solar cell.

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