

Low Power NDIR-CO₂-Sensor for Building Automation

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Abstract: Besides humidity the content of CO₂ is the most important air quality parameter in private homes. On the other hand power consumption for heating and air conditioning contributes essentially to the worldwide energy problems. An effective way to reduce it is to develop decentralized air conditioning systems consisting of optimal matched components. A major component is the air quality sensor which has not only to acquire CO₂ but also humidity and temperature. Further on such a sensor needs powerful data processing features and an interface to a bus system (either by TP or RF). The design requirements for it are different to those for sensors in industrial applications. Main targets are reliability, no maintenance and no recalibration for several years, low power consumption, small size and reasonable costs rather than high precision.

I. Introduction

Since the CO₂ content in nature is about 300 ppm and since it should not exceed 1000 ppm in office rooms for sake of concentration of the people which are working in them the metering range of an appropriate sensor should be 0 .. 2000 pm. Further requirements are listed in the following table:

Effective Range	0-2000 ppm
Accuracy	±100 ppm
Reproducibility	±50 ppm
Temperature Error	±5 ppm/K
Long Term Stability	±30 ppm/year
Home Automation System	EIB or RF
Power Consumption	< 100 mW
Temperature Range	5 ... 45 °C
Humidity Range	0 ... 95 %
Lifetime	5 to 10 years

All sensors which are on the market don't fulfil these requirements, regardless which detection principle you apply. Therefore a new sensor had to be developed.

The detection principle used is the nondispersive infrared (NDIR) spectral analysis (Figure 1). While the IR-source is an incandescent lamp with a continuous spectrum in the selectivity range the transmitted radiation energy is measured with a pyroelectric sensor mounted in line with a narrow band spectral filter, the so-called CO₂-channel. There is a second detector which receives filtered radiation in a spectrum independent of the CO₂ band, the so-called reference channel. The quotient of both signals results in a number referring to the CO₂ concentration of the measured gas.

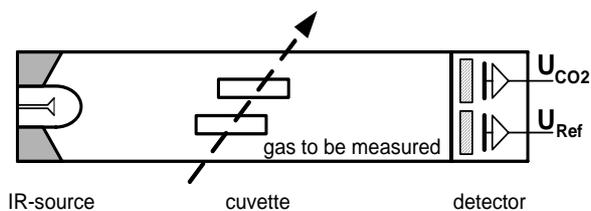


Figure 1: The Components of the CO₂-sensor, consisting of IR source, cuvette and detector.

The radiation emitted from the source is picked up with the detectors located on the opposite side of the cuvette. The energy absorption of the gas to be measured over the length of the gas cuvette is characterized by the

Lambert-Beer [1] relation in accordance with the specific absorption band of the gas. The following diagram (Figure 2) shows the transmission characteristics for CO₂ (main band approx. at 2363 1/cm) for various path length.

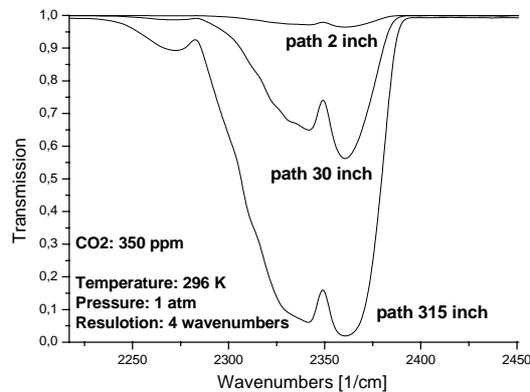


Figure 2: CO₂ Transmission lines

The transmitted radiation energy is measured with a pyro-electric sensor mounted in line with a narrow band spectral filter [2] [3]. The second detector receives filtered radiation in a spectrum independent of the CO₂ band, the so-called reference channel.

II. The Components of the Sensor System

Since different mechanical processing of the surface of the cuvette for the test systems causes big differences in radiation power which can be received by the detectors the influence of the cuvette isn't considered in this paper. In a later fabrication of this sensor the surfaces can be produced with the necessary constant properties.

A. IR-Source

Micro incandescent lamps, IR-emission diodes and micro hot plates have been tested in order to determine the best IR-source. But soon it became clear according to different reasons that the incandescent lamp is the only affordable IR-source. The broad band emissions of the lamp coil show "Black Emitter" type characteristics. The distribution of the emission intensity deviates from the "Black Emitter" characteristic curve over the wave bandwidth due to the level of absorption on the coil surface, the inhomogeneous coil temperature and filter effects of the glass bulb [12]. Figure 3 shows the values for a micro lamp sample with quartz glass bulb.

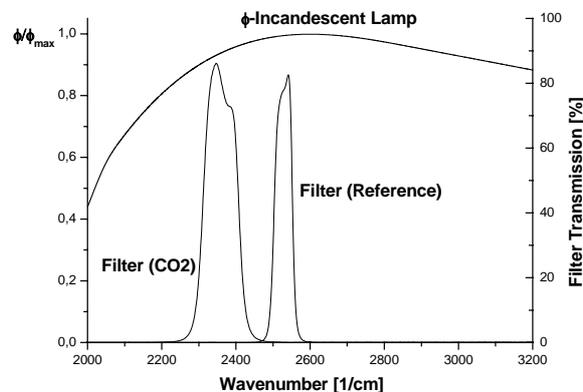


Figure 3: Emission spectrum of a quartz glass lamp against reference and CO₂ filter

Compact dimensions together with a reasonable price are advantages when micro incandescent lamps are used in CO₂ sensors applications. The main negative factor is the remarkably high energy consumption. Depending on the lamp type the average wattage ranges from 100 mW to 700 mW, limiting the operating time of battery powered sensor applications to a few hours. The high energy consumption also results in a significant thermal

radiation from the source leading to an increase in temperature in the sensor's vicinity. The temperature increase inside the cuvette and detector varies from 3°C to 10°C with respect to the installed lamp type. To increase the life time of the lamp the supply voltage can be degraded. In conjunction with a frequent change of the lamp polarity the lifetime can be extended to several years. But the high wattage of e.g. 300 mW in our testing system is the major draw back which has to be overcome by the "pulse mode". Using lamps with a lower rated current of 50mA instead of 115mA the wattage could be further reduced to 100mW.

B. Detector Design

In the "chopping mode" the IR-source is powered periodically and steady-state while in the "pulse mode" the IR-source is powered only for a very short period of time which is followed by a long pause. In this case the pulse response can be measured at the output of the detector. The evaluation of the detector response requires greater efforts in measurement and more computational power, because a bigger bandwidth has to be watched and the signal to noise ratio decreases. Prior, the main problem of a non-periodic IR-source modulation was the huge temperature drift of the pyroelectric detector using common MOSFET readout. A new multicolor detector (Figure 4) was designed with an integrated op-amp which offers a much better signal to noise ratio and a minimized temperature drift between measurement and reference channel.

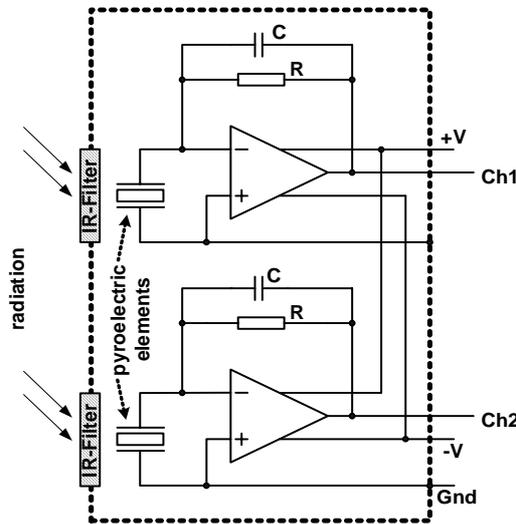


Figure 4: Schematic of an active, 2-channel pyroelectric detector.

The detector consists of two filters, two pyroelectric elements and two integrated op-amps. The detector runs in current mode which gives an almost offset-free signal. The two characterizing time constants (electrical and thermal time constant) define the behavior of the detector with respect to the modulation frequency of the IR source. In the common chopping mode the frequency response of the output signal $u_{s\Box}$ is given by the following equation (1) which interprets the pyroelectric detector as combination of high pass (thermal time constant) and low pass (electrical time constant).

$$|u_{s\Box}(j\omega)| = \alpha \tau_w \Phi_{s\Box} R \cdot \frac{p}{c'_p} \cdot \frac{1}{d_p} \cdot \frac{\omega \tau_T}{\sqrt{1 + (\omega \tau_T)^2}} \cdot \frac{1}{\sqrt{1 + (\omega \tau_E)^2}} \quad (1)$$

α is the absorption of the pyroelectric element, τ_w the transmittance of the IR filter, $\Phi_{s\Box}$ the radiation flux, R the resistance, p the pyroelectric coefficient, c'_p the volume specified thermal capacity, d_p the thickness of the element and τ_T and τ_E are the thermal and electrical time constants. The maximum signal will be achieved with modulation frequency $f_{\max\Box}$ given in equation (2).

$$f_{\max\Box} = \frac{1}{2\pi} \cdot \frac{1}{\sqrt{(\tau_T \cdot \tau_E)}} \quad (2)$$

The chopping mode results in a sinusoidal detector signal which can be measured very selectively. It eliminates almost the noise from the detector and from the electronic circuit.

In the pulse mode, the frequency response is given by equation (3):

$$|u_S(j\omega)| = \alpha \tau_w \Phi_S R \cdot \frac{p}{c'_p} \cdot \frac{1}{d_p} \cdot \left(e^{-\frac{t}{\tau_E}} - e^{-\frac{t}{\tau_T}} \right) \quad (3)$$

The maximum of the signal will be achieved after time t_{\max} given by (4):

$$t_{\max} = \frac{\ln \frac{\tau_T}{\tau_E}}{\left(\frac{1}{\tau_E} - \frac{1}{\tau_T} \right)} \quad (4)$$

To detect the pulse response a bigger bandwidth has to be watched and the signal to noise ratio decreases. Therefore, the measurement results are about 10 times less accurate than in the chopping mode. The pulse mode is also more sensitive with respect to drift and aging. Therefore an intelligent algorithm for the measurements had to be introduced.

III. Signal Processing and Measurement Results

The combination of the normal chopping mode and the newly introduced pulse mode minimizes the disadvantages of the pulse mode and enables measurements with very low power consumption. A smart microcontroller program controls the application. The comparable results are used for self-calibration and to minimize the inaccuracy of the pulse mode. The software switches between the two modes of operation at a fixed rate for recalibration or when the measured value passes a defined threshold [16]. Programmable thresholds can give feedback to the air-conditioning system or to an alarm system (Figure 5).

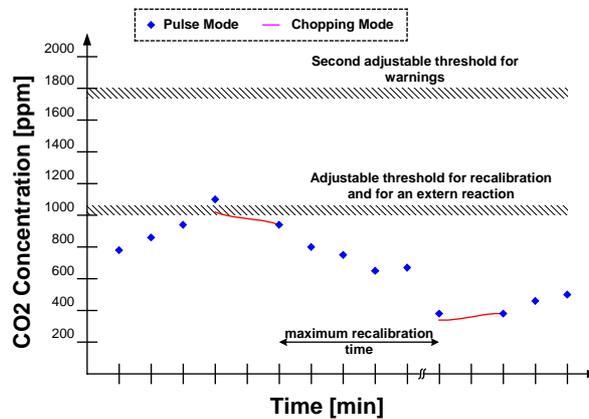


Figure 5: Timing of the measurement concept with two modes.

In pulse mode the time between single shots of radiation depends on parameters like the size of the room, the number of people in the room and which accuracy is needed.

To determine the optimum pulse length for the detector in pulse mode, several measurements with the key concentrations of 0 ppm and 2000 ppm have been carried out (Figure 6).

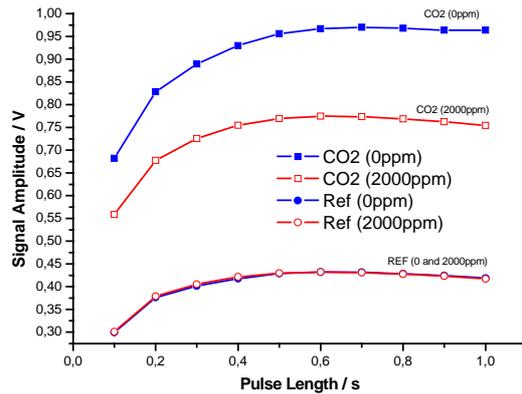


Figure 6: Sensitivity of the detector response in pulse mode for the concentration of CO₂ 0 ppm and 2000 ppm.

Figure 6 shows that a pulse length of 0.5 s offers a high sensitivity (93 $\mu\text{V}/\text{ppm}$) in the postulated range. Longer pulses only increase the power consumption without raising the sensitivity at a similar rate. The lower signal amplitude of the reference channel is caused by the IR filter which does not have the same bandwidth as the IR filter of the CO₂ channel. Figure 7 shows the time diagram of the pulse mode. The IR stimulus starts at 10 s with a duration of 0.5 s.

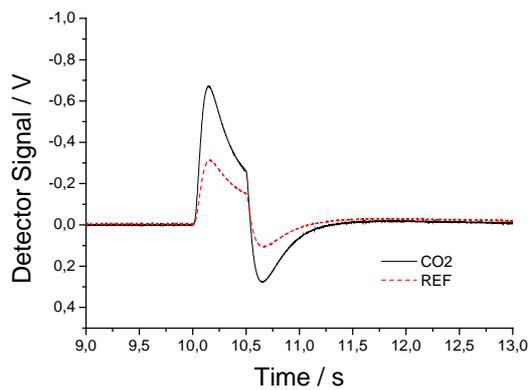


Figure 7: Time diagram of the pulse mode.

For the signal conditioning circuit it is favorable if the signal from chopping mode is in the same range as the signal from pulse mode. Figure 8 shows the detector results running in common chopping mode. The IR source is modulated by a rectangular wave. The frequency changes in a range from 0.5 Hz to 3 Hz.

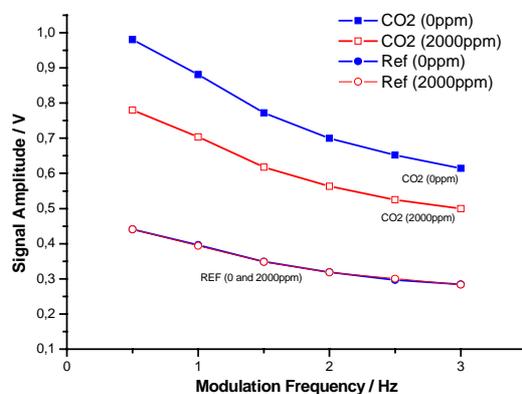


Figure 8: Sensitivity of the detector response in chopping mode for the concentration of CO₂ 0 ppm and 2000 ppm.

To enable a good noise filtering the output signal of the chopping mode should be a sinusoidal signal. In this setup a modulation frequency of 1.5 Hz achieved good results.

The aim of the CO₂-sensor should be a very low power consumption, so that the power can be supplied by e.g. the EIB bus system or by a battery. Due to the two operation modes the power consumption of the whole system depends on how often and for how long each mode is used. The power consumption of the test setup in pulse mode is as low as 20 mW on average when measuring every 5 seconds. In chopping mode the system consumes up to 300 mW. The average power consumption of our test setup was below 50 mW which could be supplied by the European Installation Bus (EIB).

IV. Future Developments and Conclusion

In the test setup a 16-Bit ADC with anti-aliasing filter and gain-control was used. In the combination of the two operational modes an accuracy between ± 15 ppm and ± 100 ppm (depending on the operation mode) was achieved which is higher than the accuracy of much higher priced sensors in the market. Since this accuracy isn't required in air-conditioning systems for private homes a sensor system is under development which uses the built-in ADC of the microcontroller with only one buffer amplifier but no analogue filter, so reducing the necessary components to a minimum. The microcontroller MSP430 is used since it features very low power consumption and the built-in ADC has 12-Bit resolution.

Further developments will focus on the following issues:

- Further decrease of power dissipation,
- Upgrading to long wave infrared until 12 μ m,
- Upgrading to 4 gas channels.

Lamp control and an optimised IR source will effect a further decrease in power dissipation. IR sources based on micro hot plates are suitable as source for long wave infrared used for gas analysis. Quad channel detectors allow the measurement of up to 3 gases, e.g. besides CO₂ also CO and water vapour. That enables the system to work as fire detection as well.

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