AN5571

Application note

Signal conditioning for NDIR sensor

Introduction

Non dispersive infrared (NDIR) is a quite old technology as the first research was carried out in 1930's in the USA by the department of defense. The commercialization of NDIR started in the 50's without never reaching big volumes mainly due to its size and output drift over the time. This technology finally reached its full potential in 2010 when new technology of NDIR appeared allowing the output to be stabilized, by reducing size and price in favor of a larger use.

Non dispersive infrared sensor is a cost effective solution to measure a large number of different gases in the range of the infrared (IR) range. It is largely used for carbon dioxide and hydrocarbon (HC) detection due to its reliability and simplicity of use.

The applications using NDIR include: the automotive to measure gas emissions, industrial to detect gas leakage but also consumer to control air quality. NDIR can also be found in medical domain to monitor patients during surgical intervention.

This application note deals with the analog signal conditioning circuit used for NDIR sensor that acts as a thermopile sensor. It explains how to condition a signal coming from a NDIR sensor, and how to improve its performance.

1 How it works

Before going into detail about the signal conditioning of a NDIR sensor, it should be useful to understand how it works. An NDIR can be considered as a thermopile, which is a serial array of thermocouples.

Based on the Seebeck principle, which is the conversion of a heat directly into electricity at the junction of different metals, the thermocouple delivers an output voltage, which in its turn depends on the temperature difference between a reference junction and an active junction.

The NDIR sensor is generally composed of a pulsed infrared source and a filter which hit the thermopile on the active junction. Under the effect of the radiation the active junction is heated. The reference junction is at the reference temperature and, in order to ensure a good stability, this reference junction is generally measured by a thermistor.

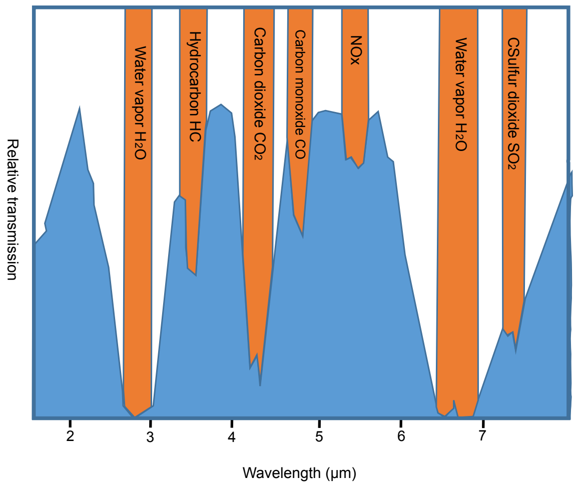
In this manner a difference of temperature between the two junctions of the thermocouple is present, which in turns generates a small voltage.

The principle is quite simple but the concentration of the targeted gas is an important data to know.

As a general physics principle, all gas molecules vibrate at a specific frequency. Absorption of IR radiation is due to vibrations of molecules. When the wavelength of the IR radiation match the target gas frequency, the gas absorbs some IR radiations, resulting in the change of the sensor output voltage.

Figure 1. Infrared gas transmission and wavelength where gases are absorbed shows below the different gas absorption wavelength in the IR domain (short-to-mid wavelength infrared).

Figure 1. Infrared gas transmission and wavelength where gases are absorbed



As per Figure 1. Infrared gas transmission and wavelength where gases are absorbed, the dioxide carbon shows a strong absorption between 4.1 µm to 4.5 µm. The maximum IR CO_2 absorption wavelength is 4.26 µm.

When an infrared light hits the thermopile, the output voltage of this one increases. The presence of a gas absorbs the IR radiation, and if a bandpass filter having the same wavelength as the gas to measure is combined to the thermopile, the output voltage and the radiation, which hits the thermopile, decrease. This is the principle of NDIR detection.

The intensity of the light hitting the thermopile is defined by the Beer's law, which relates the attenuation of light to the properties of the material through which the light travels.

It can be described as follows:

$$I = I_0 . 10^{-\epsilon l C} \quad (1)$$

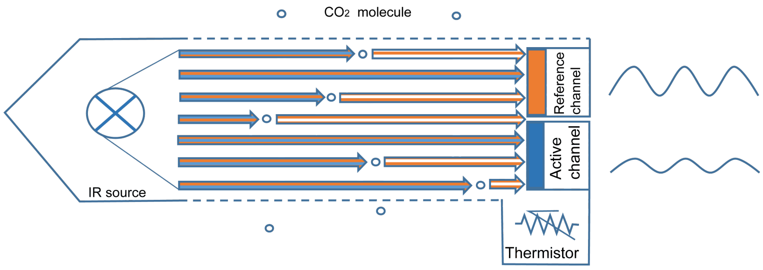
- I is the intensity of light hitting the detector (in presence of gas)
- I_0 is the intensity of light emitted by the IR source (measured without presence of gas)
- Ɛ is the molar attenuation coefficient in $L.mol^{-1}.cm^{-1}$. It depends on the wavelength, gas and the temperature

- l is the optical path length between IR source and detector in cm
- C is the molar gas concentration in mol.L-1

As l and Ɛ are fixed values defined by the sensor itself and the gas to measure once system has been calibrated, by measuring the light intensity without gas and with gas, allows the gas concentration measurement.

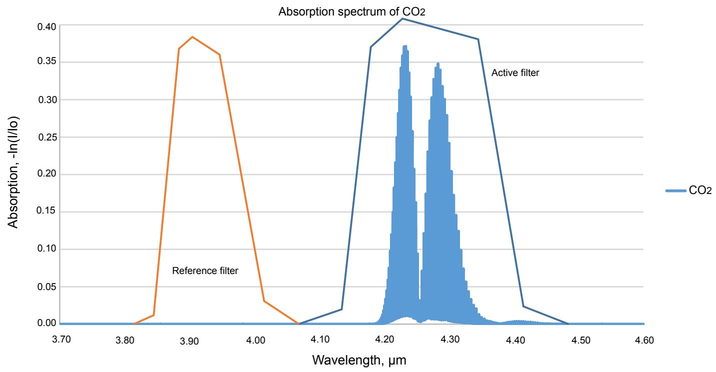
NDIR sensor is generally composed of the infrared source, optical cavity, dual-channel detector and an internal thermistor, as described by Figure 2. NDIR principle.

Figure 2. NDIR principle



Both channels are made of a thermopile, one is considered as a reference and the other one is considered as the active channel. Each channel has a specific wavelength filter. The active channel has a filter centered on the gas absorption and the reference channel on another wavelength but still in the IR range. In the case of an NDIR CO_2 sensor, the active channel is combined with a filter which allows the 4.26 µm wavelength to pass, that is the quantity the CO_2 molecule can absorb. The reference channel has a filter centered on 3.91 µm where there is no absorption as described by (data are issued by HITRAN database).

Figure 3. Absorption spectrum of CO_2



In this case even if other gases are present in the optical cavity their own IR absorption does not have any impact on the measurement. So when the targeted gas (CO_2) enters the optical cavity, the signal of the active channel decreases. Whereas it remains the same on the reference channel, as there is no IR absorbance on this wavelength.

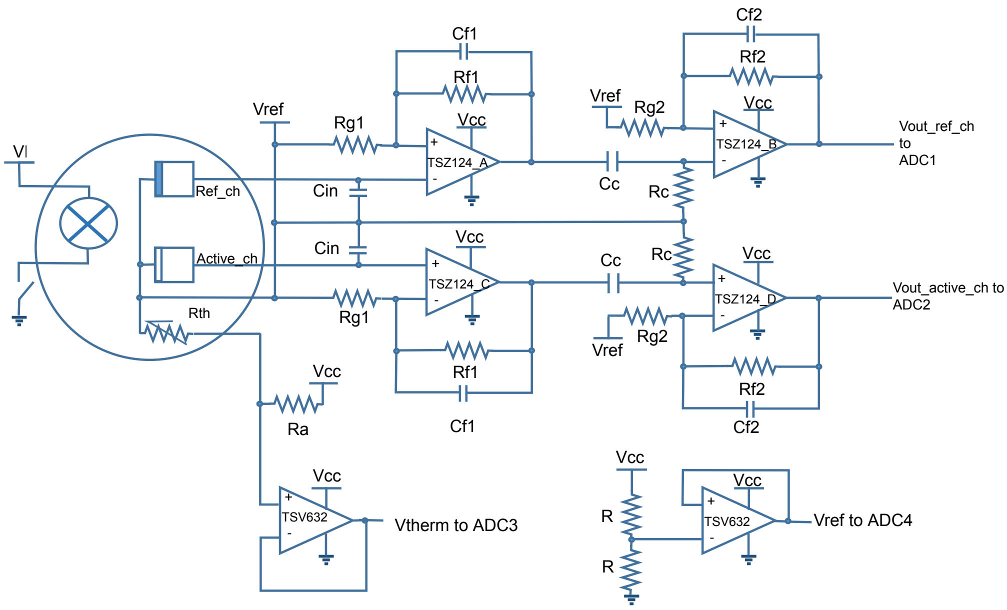
The ratio of the two-thermopile voltage (reference and active channels) gives the concentration of gas present in the optical cavity. (Note that it also allows the compensation of the aging of the IR source).

The output of the thermopile can vary depending on the ambient temperature. A thermistor is generally used to compensate this possible drift.

2 Signal conditioning

The amplification stage should exhibit a high impedance to the sensor. In order to eliminate the DC part of the signal and achieve high gain, the circuit is generally built by two gain stages and an AC coupling between them.

Figure 4. Two-stage architecture

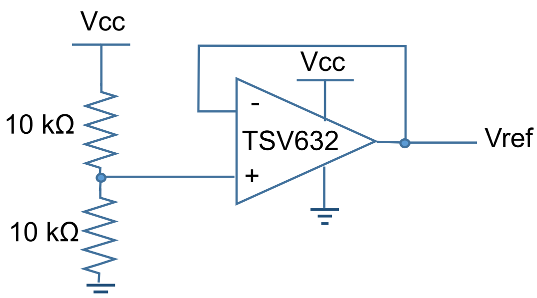


2.1 Reference voltage

Generally the output of the reference and the active channel is composed of a DC voltage more or less important depending on the NDIR sensor used. It is generally useful to provide a signal to the ADC with a ground reference. So in this case, it is simpler to power supply the op-amp with a single supply from GND to Vcc. In order not to saturate the output of the Op-amps, a reference V_{ref} preferably centered at Vcc/2 is important to use, as well as for the NDIR sensor.

It can be simply done from the Vcc power supply as suggested by Figure 5. Voltage reference V_{ref} by using the TSV632 op-amp in buffer configuration.

Figure 5. Voltage reference V_{ref}



As there is an AC coupling between the two stages, V_{ref} has to be applied on the second stage as described Figure 4. Two-stage architecture, firstly to correctly bias the op-amp and to have a DC reference avoiding any output saturation. It is also interesting to monitor the Vref thanks to an ADC in order to eliminate any error related to the resistors and op-amps.

2.2 Gain

The AC gain of this schematics, for one channel, following the architecture described in Figure 4. Two-stage architecture can be written as follows:

$$Gain = \left(1 + \frac{Rf1}{Rg1}\right) . \left(1 + \frac{Rf2}{Rg2}\right) \tag{2}$$

To limit the noise, most part of the gain must be fulfilled on the first stage. Rf1 and Rf2 can be chosen with the same value as well as for Cf1 and Cf2, in order to have the same low-pass filter cut-off frequency on both stages. Once Rf and Cf values are chosen, the gain can be set with Rg1 and Rg2. As mentioned, to optimize noise performance it is recommended to choose Rg1 much lower than Rg2.

As the system is calibrated, the gain error due to the mismatch of the resistance is compensated. As the measurement is a ratio of the active channel and reference channel, if the resistances used for the gain are made of the same material, the temperature coefficient of the resistance does not have any impact on the precision of the measure.

The output signal of one channel of the schematic Figure 4. Two-stage architecture can be described by the equation below:

$$Vout = Vchannel\left(1 + \frac{Rf1}{Rg1}\right)\left(1 + \frac{Rf2}{Rg2}\right) + Vref \tag{3}$$

Vchannel represents the voltage on the output either of the active channel or of the reference channel of the NDIR sensor.

2.3 Bandwidth

The pulsed light of the IR source of the NDIR sensor works generally at a very low frequency (few Hz). It is important to limit the bandwidth of the application as much as possible in order to limit the noise. A first order low pass filter is realized thanks to the RC network. Rf1.Cf1 with a -3 dB cut-off frequency:

$$f1 = \frac{1}{2\pi . Rf1 . Cf1} \tag{4}$$

Another first order low-pass filter is realized thanks to the RC network. Rf2.Cf2 with a -3 dB cut-off frequency:

$$f2 = \frac{1}{2\pi . Rf2 . Cf2} \tag{5}$$

So the overall circuit acts as a second order low-pass filter.

In addition the internal resistance of the thermopile of the NDIR sensor (generally hundreds of kΩ) can be used to make an additional low-pass filter. It is recommended to use a cut-off frequency close to f1 and f2. So it allows a low-pass filter of 3^{rd} order to be got at the system level.

$$f3 = \frac{1}{2\pi . Rint . Cin} \tag{6}$$

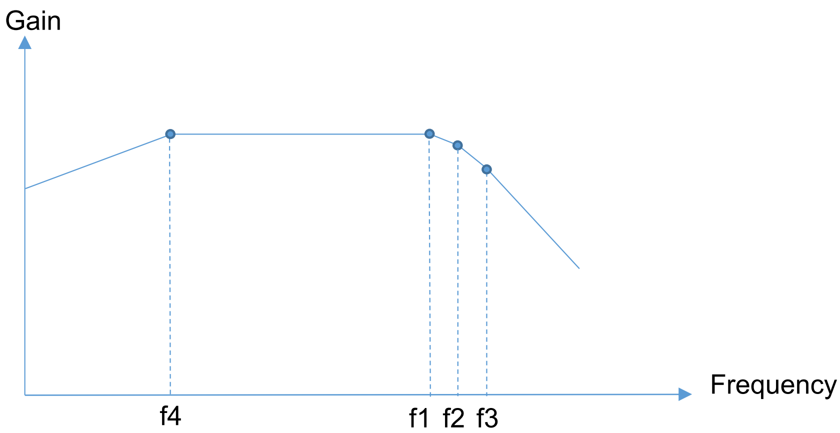
The AC coupling is due to the serial capacitance Cc, which removes all DC components introduced by the NDIR sensor itself and the first stage op-amp. In order to ensure the biasing of the second stage op-amp, a resistance Rc is added. The RC network Rc.Cc forms a high-pass filter with a cut-off frequency:

$$f4 = \frac{1}{2\pi . Rc . Cc} \tag{7}$$

The -3 dB cut-off frequency filter should be selected as low as possible in order to not disturb the functionality of the NDIR (generally hundreds of mHz).

Figure 6. Representative transfer function of the schematics below gives an idea of the transfer function of the Figure 4. Two-stage architecture. It may vary depending on the chosen cut-off frequencies of the application.

Figure 6. Representative transfer function of the schematics



2.4 Noise

The noise is a predominant error source as it cannot be calibrated and so must be limited as much as possible by choosing low resistances and an op-amp with a very low noise in low frequency.

The NDIR sensor works at low frequency (few Hz), the TSZ124 op-amp chosen to drive this sensor is a perfect choice as it is a chopper amplifier. Contrary to traditional op-amp, the TSZ124 has no 1/f noise, it has only a white noise of 40 nV/√Hz or 0.7 µVpp from 0.1 Hz to 10 Hz, which is generally in the range of the NDIR sensor noise.

It is also interesting to have a look at the whole noise of the application as the one described by Figure 4. Two-stage architecture.

The following equation is the input referred noise of the circuit without considering the noise of the sensor itself. In the following equation, the noise expressed in Vrms, is integrated over the working frequency bandwidth, which is defined thanks to the filter cut-off frequency f1 and f4. It is a first order calculation in order to have an idea of the error due to the noise (the filter is considering as a brickwall).

$$Vin\,noise\,Rms = \sqrt{\int_{f1}^{f4}\left[\frac{en_1^2.\left(1+\frac{Rf1}{Rg1}\right)^2+4KTRg1.\left(\frac{Rf1}{Rg1}\right)^2+4KTRf1}{\left(1+\frac{Rf1}{Rg1}\right)^2}+\frac{4KTRc}{\left(1+\frac{Rf1}{Rg1}\right)^2}+\frac{en_2^2\left(1+\frac{Rf2}{Rg2}\right)^2+4KTRg2.\left(\frac{Rf2}{Rg2}\right)^2+4KTRf2}{\left(1+\frac{Rf1}{Rg1}\right)^2\left(1+\frac{Rf2}{Rg2}\right)^2}\right]df} \quad (8)$$

In order to limit the noise error the highest gain is done on the first stage of the schematic Figure 4. Two-stage architecture, thus the third term of Eq. (8), which represent the noise generated by the second stage of the schematic can be neglected. Also considering that Rf is much bigger than Rg1, Eq. (8) can be simplified as follows:

$$Vin\,noise\,Rms = \sqrt{\int_{f1}^{f4}\left[en_1^2. + 4KTRg1.\left(1+\frac{RcRg1}{Rf1^2}\right)\right]df} \quad (9)$$

- Where K is the Boltzmann's constant ($1.38.10^{-23}JK^{-1}$)
- T is the temperature in °K

2.5 DC parameter VIO

As the first stage is AC coupled, the input offset error of this amplifier is not really a significant parameter.

Only Vio of the second stage op-amp is multiplied by the lower gain.

Moreover by using the TSZ124 op-amp which exhibits a Vio = 8 µV overtemperature, there is no chance to saturate the output. As the TSZ124 is a chopper amplifier, the drift of the Vio vs. temperature is extremely low (30 nV/°C) and even after a calibration @25 °C, it does not affect the measurement during the whole life of the NDIR application.

Also, generally the active and reference channel measurement is a peak-to-peak measurement, allowing the offset to be nulled.

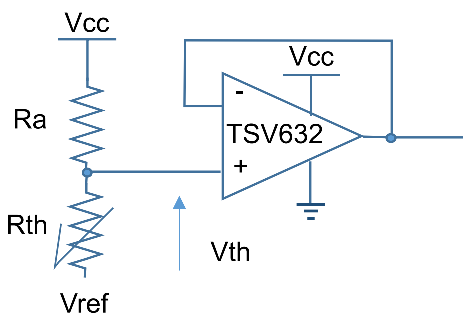
2.6 Thermistor

The IR_{source} light increases the temperature inside the cavity compared to the ambient temperature. In order to compensate any drift, it is important to monitor the temperature at the same time as the voltage on the active and reference channels.

This is the goal of the thermistor generally integrated in the NDIR sensor.

See Figure 7. Thermistor circuit.

Figure 7. Thermistor circuit



The voltage across the thermistor can be described by the following equation:

$$Vth = (Vcc - Vref)\,.\,\frac{Rth}{Rth + Ra} \tag{10}$$

- Where Rth is the thermistor value in temperature. This Rth value can be given by the NDIR sensor datasheet and in this case, the temperature close to the channel can be deduced by the equation Eq. (11)

$$T(°C) = \frac{\beta}{\frac{\beta}{T0} + \ln\left(\frac{Rth}{Ramb}\right)} - 273.15 \tag{11}$$

with

- β is given by the NDIR sensor datasheet
- Ramb is the value of the thermistor
- T0 is the ambient temperature expressed in K (298.15 °K)

Combining equation 10 and 11 leads to:

$$T(°C) = \frac{\beta}{\frac{\beta}{T0} + \ln\left(\frac{Ra/Ramb}{\frac{Vcc - Vref}{Vth} - 1}\right)} - 273.15 \tag{12}$$

The TSV632 op-amp is used as a buffer and it helps to absorb charge impact due to the ADC sampling before entering the ADC.

2.7 Application examples

A series of examples of NDIR application are going to be displayed, by using CO_2 sensor from Alphasense IRC-AT.

This is a CO_2 sensor able to deliver a maximum signal on the active channel of 7 mVpp. The IR light integrated into the sensor is driven by a PWM generated by a microcontroller STM32 with a frequency of 3 Hz and a duty cycle of 50%.

The STM32 microcontroller power supply with 3.3 V is also used to digitalize and treat the analog signal.

So the gain of the circuit should not exceed 470.

1/ gain and band pass of the system

The IRC-AT sensor channel generates an AC signal combined with a typical DC voltage of 9 mV so an AC coupling path as described by the Figure 9. Application schematic using IRC-AT sensor with two gain stage is chosen to remove this DC voltage.

The first stage gain is set at 47 V/V and the second stage to 10 V/V which allows a total gain of 470. The cut-off frequency of the low pass filter f1 and f2 is set to 19 Hz to not impact the input signal of 3 Hz and limit the noise.

This cut-off frequency has also been chosen to limit the impact of the 50 Hz/60 Hz on the application as the NDIR sensor impedance is generally high (~60 kΩ).

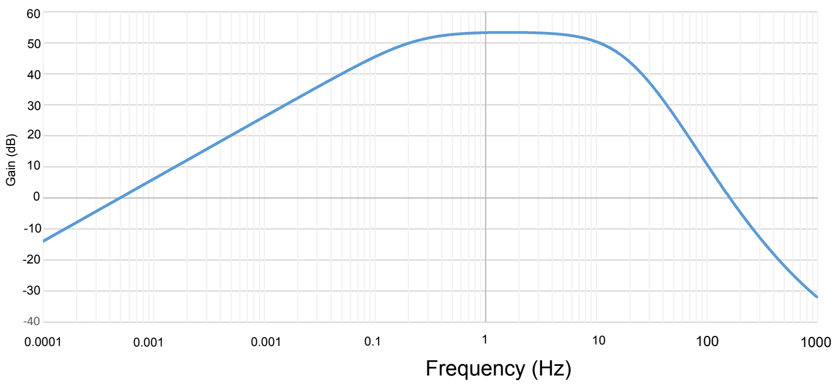
The internal resistor based on our measurement of the active channel and reference channel is roughly 60 kΩ.

Combine with a capacitance of 100 nF it creates another low-pass filter with a cut-off frequency of 26 Hz according to the Eq. (6).

The high-pass filter helping to remove DC voltage is chosen as low as possible, around 200 mHz.

Figure 8. Frequency response of the application shows the frequency response of the application described by Figure 9. Application schematic using IRC-AT sensor.

Figure 8. Frequency response of the application



The IR source of NDIR sensor is pulsed at 3 Hz and we can see in Figure 8. Frequency response of the application that the gain is maximum (53 dB) at this frequency.

2/ noise of the system

By considering the source impedance of 60 kΩ, at first order a thermal noise of 31 nV/√Hz generated by a channel of the NDIR sensor.

Noise of the TSZ124 is 40 nV/√Hz, so it is the same order of magnitude.

3/ divider bridge for thermistor

The table below issued from Alphasense datasheet helps to calculate the value of the internal thermistor Rth versus temperature for the sensor IRC-AT.

$$Rth = R_{25} \, . \, e^{\beta\left(\frac{1}{273.15 + T°C} - \frac{1}{298.15}\right)} \tag{13}$$

β = 3940 K

R_{25} = 100 kΩ

It is helpful to correctly choose the value of the external resistance Ra

Table 1. Thermistor resistance vs. temperature of IRC-AT sensor

Temperature (°C)	R(Ω) +/-5%
-30	1.99 M
-25	1.43 M
-20	1.05 M
-15	775 k
-10	580 k
-5	439 k
0	335 k
5	259 k
10	201 k
15	158 k
20	125 k
25	100 k
30	80.4 k
35	65.1 k
40	53.1 k
45	43.6 k
50	36 k
55	29.9 k
60	24.9 k

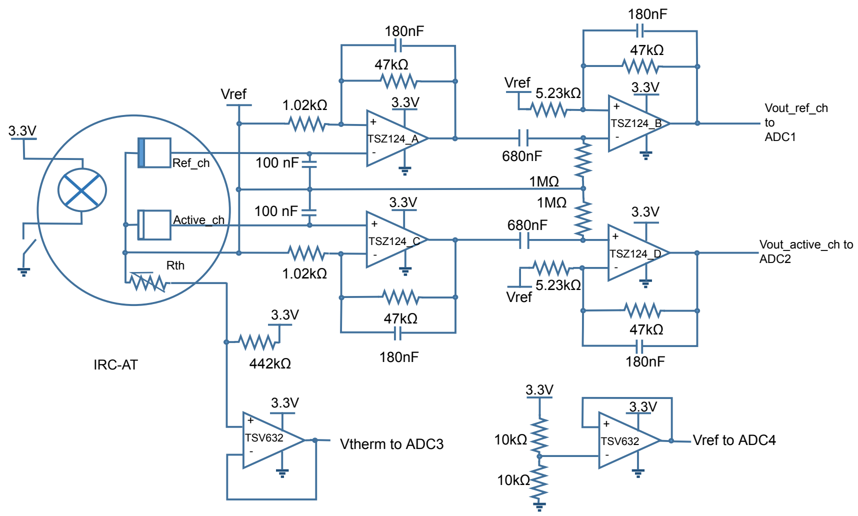
The worst case in order to size correctly the application, the maximum R_{th} at -30 °C is 1.99 MΩ. In order to be as accurate as possible it is better to work with the full range ADC. In order to avoid any saturation, consider a maximum output voltage Vtherm of 3 V.

Thanks to Eq. (14) we can calculate the value of the Ra resistance:

$$Ra = \frac{(Vcc - Vtherm).Rth}{Vtherm - Vref} \quad (14)$$

Ra can be chosen at 442 kΩ.

Figure 9. **Application schematic using IRC-AT sensor**

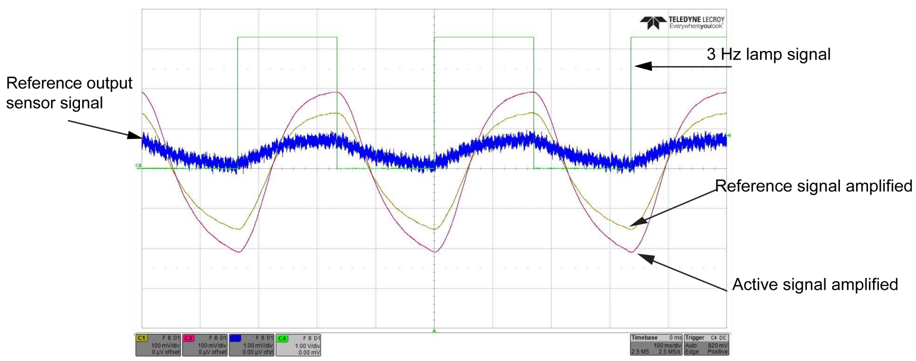


The Figure 10. Probe scope of the application shows a probe scope of the application described by Figure 9. Application schematic using IRC-AT sensor as measured in the lab.

The test has been carried out in ambient air without sensor calibration.

The reference output sensor signal (blue curve) exhibits a noisy signal of 600 µVpp. The output signal of reference (yellow curve) and active channel (red curve) are well-filtered and amplified by 470.

Figure 10. **Probe scope of the application**



The Figure 12. Probe output channel with CO_2 concentration higher than normal level shows the behavior of the channel when the sensor is used in area where CO_2 concentration is higher than normal level. The reference channel amplitude remains at the same level, whereas the amplitude of the active channel decreases as the CO_2 concentration increases.

Figure 11. Probe output channel in ambient air

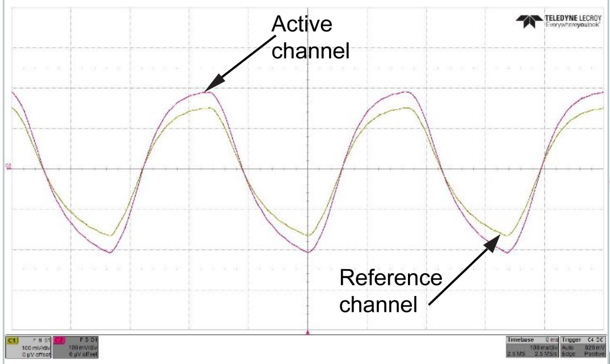
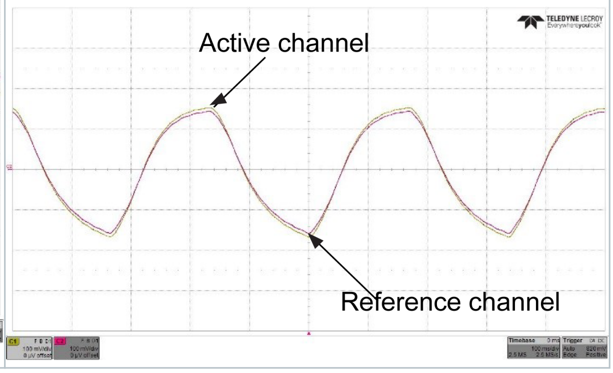


Figure 12. Probe output channel with CO_2 concentration higher than normal level



3 Conclusion

NDIR sensor provides an extremely small voltage depending on the gas concentration.

Amplifying this analog signal generally requires two stages of amplification.

Some of NDIR sensors have a quite high intrinsic DC voltage, thus an AC coupling architecture allows this offset to be removed. Moreover, an NDIR sensor must be calibrated before use, and so the DC error introduced by the electronics is not the most blocking point. On the other hand, the noise cannot be calibrated as it is a non-periodic signal, and a particular attention must be paid on this parameter.

The NDIR sensor works generally at low frequency and the big advantage of the use of a chopper amplifier such as the TSZ124, is that it does not present any 1/f noise in low frequency, allowing good performance and precision measurement. However, it is necessary to limit the bandwidth of the system in order to limit the noise as well.

To complete the whole architecture, the TSV632 op-amp can be used as buffer for the thermistor and voltage reference.

Revision history

Table 2. **Document revision history**

Date	Version	Changes
29-Oct-2020	1	Initial release.

Contents

List of tables

List of figures