Temperature Behaviour

Sources and implications of thermal effects on detector behaviour

InfraTec.

Temperature Behaviour and Temperature Compensation

Due to the excellent properties of lithium tantalate, pyroelectric detectors based on this material have a high responsivity and a good signal-to-noise ratio without additional cooling or temperature stabilisation. With a Curie temperature of 603 °C, lithium tantalate keeps its pyroelectric property far beyond the operating temperature range specified for the detectors. Therefore, the properties of the components used in the detectors and their packaging determine the limits of the operating and storage temperature. However, even within these limits the properties of the detectors change slightly because of the temperature dependencies of the electronic components. When speaking about the "temperature coefficient of a detector", we should always keep in mind that the detector is a complex system. Its temperature behaviour cannot simply be characterised by specifying a single numerical value as would be the case with simple, passive components.

3.1 Causes

To describe the temperature behaviour of a pyroelectric detector, it is necessary to consider the behaviour under quasi-stationary conditions as well as with changes in the ambient temperature.

In a system thermally settled the temperature dependencies of the individual components used in the detector overlap depending on their wiring and the modulation frequency selected with respect to the individual application.

Changes in the ambient temperature over time are typically low frequency processes which are superimposed on the modulated detector signal and lead to an unstable or variable offset voltage. The reason for this is that a change in the housing temperature also causes a very slow change in the temperature of the pyroelectric chip. However, such temperature changes are significantly larger and of longer duration than those caused by a typical radiation source. Consequently, a low frequency signal with a possibly very high amplitude is generated which may cause the detector signal to saturate.

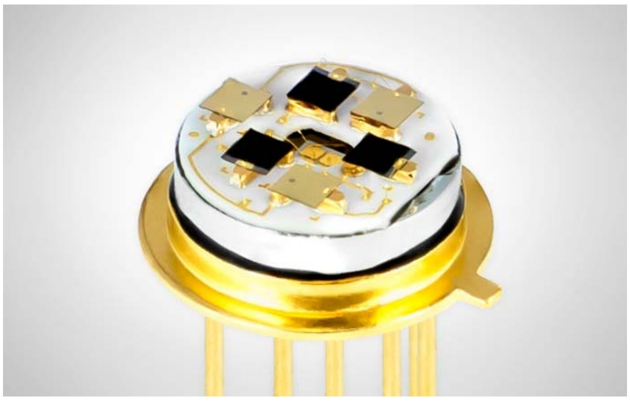


Figure 14: Additional chips for thermal compensation (without black absorbing layer)

A way of dealing with these temperature-related fluctuations of the offset voltage is thermal compensation. For this purpose, a second pyroelectric element of the same size which is insensitive to the impinging radiation is connected antiparallel to the active element. In the case of an external temperature change equally sized charges of different polarity are generated in both elements which mutually compensate each other. Thus, the influence of an external temperature change to the offset voltage can be reduced significantly.

Since the temperature dependency in the steady state and the signal fluctuations during temperature changes have different causes, they must be considered separately. Different methods are required to suppress the effects efficiently.

3.2 Components

The components used in a pyroelectric detector are described below with respect to their temperature dependency. Based on this knowledge, we will interpret the experimentally determined dependencies of selected detector characteristics regarding temperature as a next step. Figure 15 illustrates the components that contribute significantly to the temperature dependence of a detector.

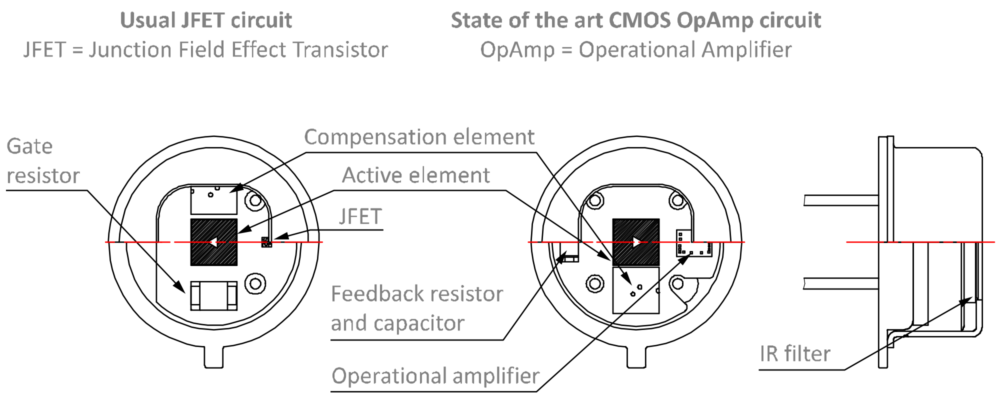


Figure 15: Temperature-dependent components in a pyroelectric detector

Pyroelectric Material

The Curie temperature of the pyroelectric material is a crucial parameter for the pyroelectric conversion. If this temperature is exceeded, a phase transition takes place in the material in which case its permanent polarisation is lost.

InfraTec uses only monocrystalline lithium tantalate as pyroelectric material. It has the advantages of low noise in the low frequency range as well as a Curie temperature of 603 °C. As a result, there is practically no risk of depolarisation of the material even at temperatures above the detector's operating temperature range.

Within the specified temperature range, the intrinsic temperature coefficient of the pyroelectrically generated current is particularly meaningful for the temperature behaviour of the detector. In the case of lithium tantalite, it has a typical value of 3,800 ppm/K in the temperature range of -25 … 85 °C.

The pyroelectric material is typically coated on one side with a layer which is "black" in the infrared spectral range to improve the conversion of radiation into temperature. InfraTec uses two different technologies for this. Detectors with the black metal coating, which is particularly uniform over a wide wavelength range, will be damaged irreversibly at temperatures over 60 °C. Therefore, the maximum operation and storage temperatures are slightly lower for these detector types.

The radiation impinging on the pyroelectric element causes a change in the quasi-stationary chip temperature. A settling time is required after starting the irradiation until the average chip temperature is no longer changing. The settling time depends on the heat capacity of the pyroelectric chip and its mounting as well as on the connection of these components to the environment. The irradiated power and ambient temperature have an impact on the settling time as well.

Temperature Behaviour and Temperature Compensation

Passive Components

Resistors
The high value resistors used as gate or feedback resistor have a strong negative temperature coefficient (TC) of their resistance value. A typical TC for 100 GΩ resistors as used in InfraTec detectors is -2,000 ppm/K. This change in the resistance affects the performance of the detector differently depending on the operating mode. Detailed explanations are given in section 3.3.

Capacitors
The capacitors used in current mode are implemented by either printed parallel conductor tracks or NP0[1] capacitors depending on the nominal value. These components have an extremely low temperature coefficient which means that the temperature-dependent change of the capacitance has no measurable influence on the behaviour of the detectors.

Active Components

The transfer behaviour of the JFET is primarily influenced by two opposite temperature dependencies (cf. Figure 16):

- Firstly, a higher temperature causes a decrease of the depletion zone of the p-n transitions which is expressed as a decrease in the pinch-off voltage (approx. -2 mV/K). Consequently, the drain current increases with a constant gate source voltage with increasing temperature.
- Secondly, the mobility of the charge carriers decreases with a higher temperature (~ 0.7 ppm/K) because stronger lattice vibrations increasingly impede the current flow. As a result, the drain current drops.

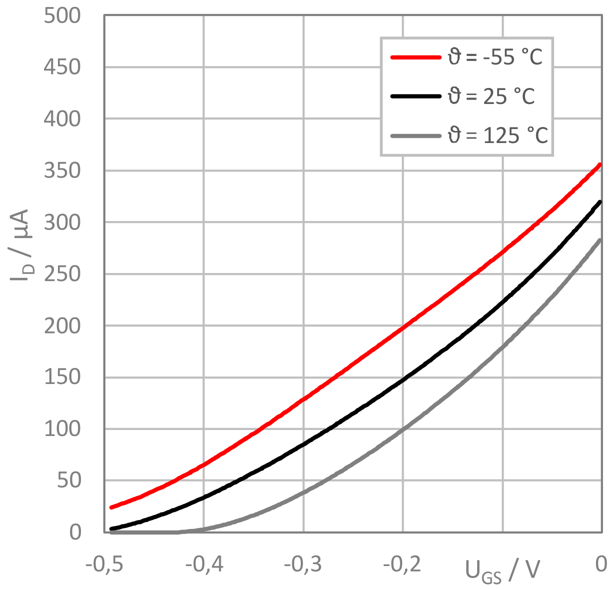


Figure 16: Typical transfer characteristics of the JFET at different temperatures

Furthermore, the gate leakage current and the input current noise of JFETs increase exponentially with rising temperature. Thus, the typical leakage current of a JFET is significantly less than 1 pA at room temperature while at 125 °C it can increase to well above 10 pA.

[1] Common term for class 1 ceramic capacitors with a nominal TC of 0 ppm/K

The results of these temperature effects and possible measures to reduce them will be discussed in more detail in section 3.3.

Integrated Operational Amplifiers
The integrated OpAmps used at InfraTec were chosen for their low input bias current and low input voltage noise density. Like with all other semiconductor components, the input bias current of the OpAmp increases disproportionately with increases in temperature.

However, the input bias current is still quite low in the operating temperature range of a pyroelectric detector and only starts to rise sharply from approx. 85 °C as Figure 17 illustrates. Other parameters such as the open loop gain vary with temperature as well, but this does not affect the detector behaviour due to the strong negative feedback of the circuit.

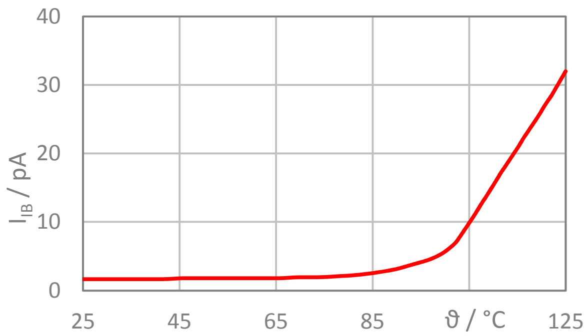


Figure 17: Input bias current of the OpAmp as a function of the ambient temperature

Optical Filters
The temperature behaviour of optical filters and windows also contributes to a temperature-dependent change in the responsivity of the detector. The relevant parameters and the effects of a temperature change on the spectral behaviour of infrared filters are described in detail in the chapter "Filters and Windows" of the InfraTec product catalogue.

3.3 Effects on the Detector Behaviour

In most applications, a voltage proportional to the pyroelectrically generated current is measured at the detector output but not the current itself. As described in section 1, the current is converted into a voltage depending on the operating mode. Thus, the thermal effects of the internal circuit and the pyroelectric conversion overlap which leads to different results depending on the operating mode.

The results of measurements using a very simple test setup are illustrated in the following chapter. They are intended to show how the individual detector parameters depend on the ambient temperature and its rate of change. The test setup consisted of a thermostatically controlled detector holder and a black body source at a temperature of $T_{BB} = 500\ K$. A mechanical chopper was used for modulating the radiation. While the detector was temperature-controlled, the chopper was operated at room temperature. All measured values shown are typical values from which the measured values of individual detectors can deviate.

3.3.1 Voltage Mode with JFET

Responsivity

As shown in equation (27), the responsivity at sufficiently high modulation frequencies (> 2 Hz) depends on material parameters and mechanical dimensions and decreases with 1/f in voltage mode. Of these parameters, the pyroelectric coefficient p, the specific heat capacity c_p, the mass density ρ and the relative dielectric constant ε_r are dependent on the temperature and affect the temperature behaviour of the detector.

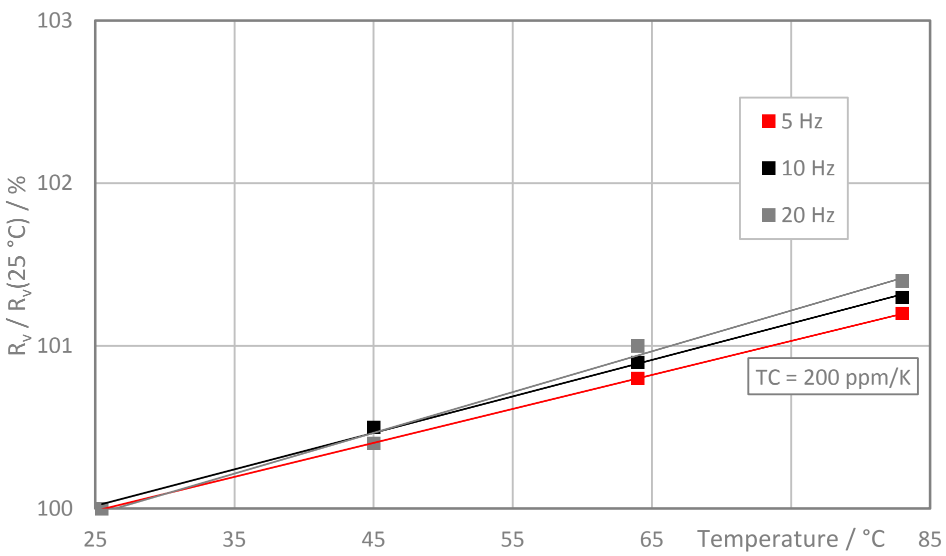


Figure 18: Change in the responsivity of an LME-302-61 with changing ambient temperature and modulation frequencies

Figure 18 shows the results of measurement for an uncompensated detector LME-302-61 at different modulation frequencies.

Based on theoretical considerations as well as the above measurements and without considering the optical filter, the temperature coefficient of detectors in voltage mode typically lies within the range of -1,000 … 500 ppm/K.

Temperature Behaviour and Temperature Compensation

Noise

The gate leakage current of the JFET increases exponentially with increases in temperature as mentioned under the heading “Active components”. Since the gate leakage current and the current noise density are directly proportional according to (30), the current noise density N_I increases exponentially as well.

Therefore, the current noise density can have a dominant influence on the overall detector noise for detectors with sufficiently large gate resistances and thus low thermal noise. The noise density then increases exponentially with temperature.

Offset Voltage

The discussion in section 3.2 implies that the offset voltage which is superimposed on the measurement signal in voltage mode also changes with temperature. The reduction of the pinch-off voltage, the reduction of the gate resistance and the increase of the gate leakage current with increasing temperature are responsible for this. Since the leakage current increases much more than the remaining parameters, the offset voltage of a detector in voltage mode always increases with increasing temperature.

If the ambient temperature changes over time, a low frequency voltage with varying amplitude which may be very high is superimposed on the offset voltage. As a result, the output voltage can increase up to the level of the supply voltage and saturates. Due to the large electrical time constant τ_{el} typical for voltage mode, it sometimes takes a very long time until the offset voltage of such a detector settles to a steady state again. By selecting a low gate resistance, however, the voltage amplitude generated by the temperature change is lower and the output signal settles faster again due to the smaller electrical time constant.

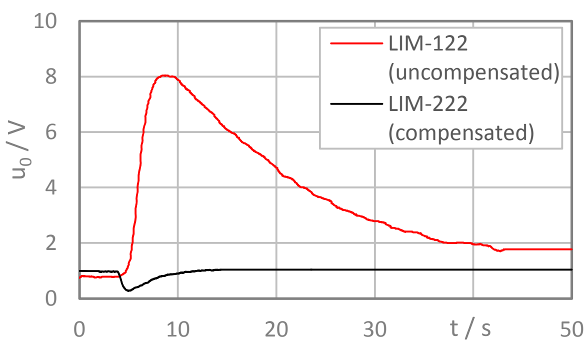


Figure 19: Time sequence of the offset voltage after a rapid increase in temperature for different voltage mode detectors

Another possibility to minimize the fluctuations of the offset voltage due to temperature changes is thermal compensation. Here, as described in section 3.1, a second radiation-insensitive pyroelectric chip is connected to the radiation-sensitive, active chip in such a way that the pyroelectric currents caused by changes in the ambient temperature mutually compensate each other.

Figure 19 shows the impact of this compensation on the offset voltage. For this purpose, a compensated and an uncompensated detector were exposed to a rapid change in the ambient temperature. It is obvious that the thermal compensation significantly reduces the influence of the temperature change on the offset voltage. The amplitude is reduced, and the thermal settling time is shorter. Perfect compensation is not possible though due to technical tolerances. The change of the offset voltage can be positive or negative depending on whether the charges are predominantly generated by the radiation-sensitive element or by the compensation element.

Temperature Behaviour and Temperature Compensation

There are two different ways to connect the active element to the compensating element as Table 6 shows. In both cases the additional electrical capacitance of the compensation element changes the electrical behaviour of the detector in voltage mode.

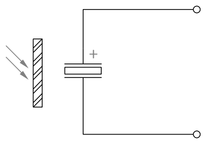
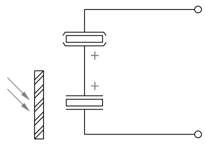
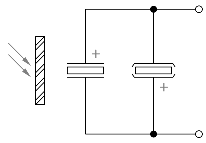
	No compensation	Serial compensation	Parallel compensation
Circuit			
Signal	100 %	100 %	50 %
Noise	100 %	170 %	70 %

Table 6: Comparison of the detector parameters under the influence of thermal compensation in voltage mode

Serial compensation has the advantage of offering twice the output signal compared to parallel compensation. This is offset by lower stability of the operating point in particular during long-term temperature ramps. Therefore, the use of serial compensation is uncommon. In addition, the achievable signal-to-noise ratio of typically 1/170 % = 59 % of an uncompensated detector is more than 15 % worse than the theoretical value of $\frac{1}{\sqrt{2}}$. That is why, we highly recommend to use parallel compensation for a stable operation in fast temperature ramps (> 2 K/min) as well as for a low signal drift during long-lasting heat-up or cool-down processes especially since the signal-to-noise ratio almost reaches the theoretical value of 70 % even in series production.

3.3.2 Current Mode with OpAmp

Responsivity

In current mode the pyroelectric element is virtually short-circuited and the pyroelectric current flows through the feedback path. Thus, the temperature dependency is determined by the pyroelectric coefficient p, specific heat capacity c_p, mass density ρ and feedback resistance R_{fb}. The latter also changes the electrical time constant τ_{el} which is why the temperature coefficient of a detector in current mode depends on the modulation frequency as well. A modulation frequency far above the electrical corner frequency f_{el} results in a temperature coefficient of approx. 2,000 ppm/K. With a modulation frequency below the electrical corner frequency f_{el}, the influence of the strong negative temperature coefficient of the feedback resistance increases constantly. Thus, the temperature coefficient of the detector decreases with lower modulation frequencies.

The detector LME-335 has an electrical time constant of $20\ \mathrm{ms}$ and thus an electrical corner frequency of $f_{el} \approx 8\ \mathrm{Hz}$. It was measured as an example. Figure 20 shows the changes of the temperature coefficient of the responsivity with the modulation frequency.

Temperature Behaviour and Temperature Compensation

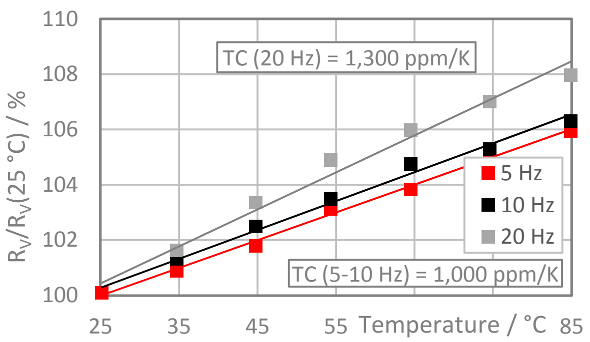


Figure 20: Temperature coefficient of the responsivity of the LME-335

Independent of the modulation frequency, typical temperature coefficients for detectors in current mode are -500 … 2,000 ppm/K without considering the temperature coefficients of optical filters.

Noise

The input bias current and feedback resistance represent temperature-dependent noise sources of detectors in current mode. They cause a strong increase in the noise density in particular with high feedback resistances and low frequencies as shown in Figure 21.

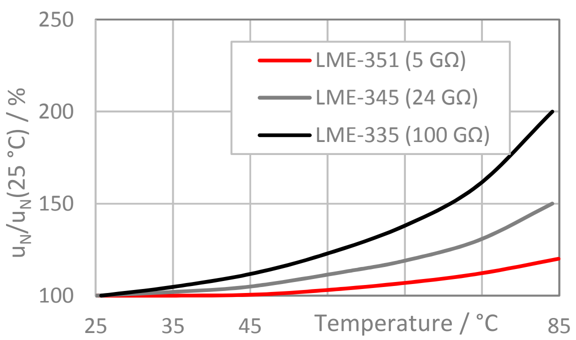


Figure 21: Increase in noise density for selected current mode detectors depending on temperature

Temperature Behaviour and Temperature Compensation

Offset Voltage

As Figure 22 illustrates, the offset voltage of a detector with an OpAmp consists of the offset voltage u_{OS} of the OpAmp itself and the voltage drop which the input bias current I_{IB} causes across the feedback resistance R_{fb}. Even though both parameters are dependent on temperature, the influence of the input bias current should be considered as dominant because of the high feedback resistances. Therefore, at high temperatures, offset voltages in the range of several 100 mV can occur with detectors using high feedback resistances.

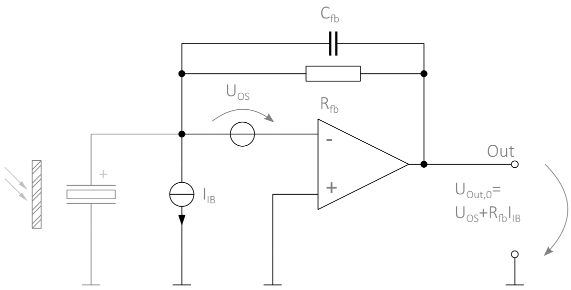


Figure 22: Relevant influencing factors of the offset voltage for current mode detectors with OpAmp

Figure 23 shows how the feedback resistance and temperature affect the offset voltage.

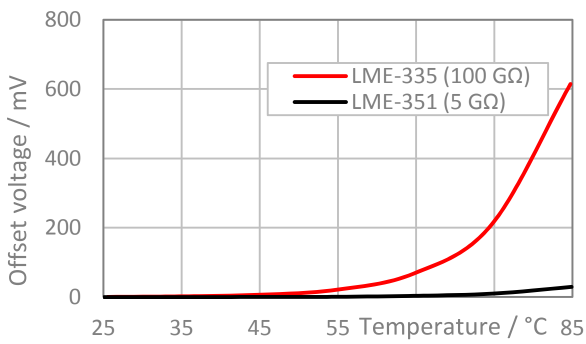


Figure 23: Impact of different feedback resistances of current mode detectors on offset voltage changes depending on temperature

With changes in the ambient temperature of the current mode detector, a low frequency signal of high amplitude is generated which overlays the modulated measurement signal. To largely suppress this signal, there is the option of thermal compensation in current mode as well. Unlike in voltage mode, only parallel thermal compensation is possible since the resulting increase of the capacitance at the input of the OpAmp only has a very minor impact on the detector's electrical behaviour.

Another simple measure to reduce the effects of temperature changes on the offset voltage is the substantial reduction of the feedback resistance. The lower amplification ensures that temperature-dependent signal changes are less amplified, too. This improvement of the temperature behaviour, however, causes a reduction in the responsivity of the detector. As an example, three detectors in different combinations of thermal compensation and feedback resistance were exposed to a rapid change in temperature. The results of measurement illustrated in Figure 24 indicate that both measures can either be used individually or together.

Temperature Behaviour and Temperature Compensation

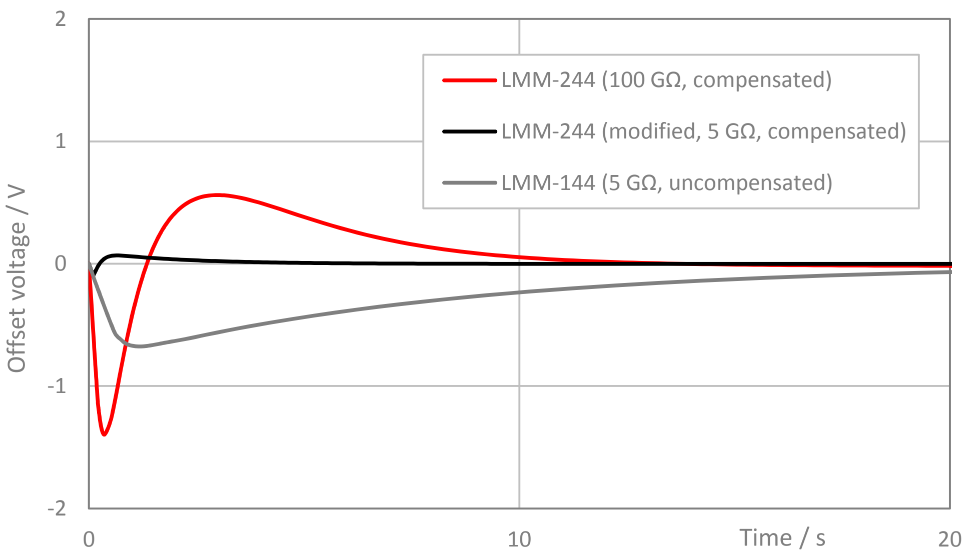


Figure 24: Settling behaviour of the offset voltage after a rapid increase in temperature

3.4 Summary and Comparison

When choosing an optimum detector for a specific application, the temperature behaviour plays an important role. The temperature behaviour under stable conditions and the reaction of the detector to temperature changes are of interest in this context.

Regardless of the operating mode, the leakage currents of the amplifier elements increase disproportionately with increasing temperature. This results in a corresponding increase in noise and offset voltage with temperature.

The temperature coefficients of the responsivity strongly tend to be negative values in voltage mode (up to approx. -1,000 ppm/K). In current mode the values are more positive (up to approx. 2,000 ppm/K). Here, the temperature coefficients of the responsivity are significantly influenced by the modulation frequency and its position relative to the electrical corner frequency.

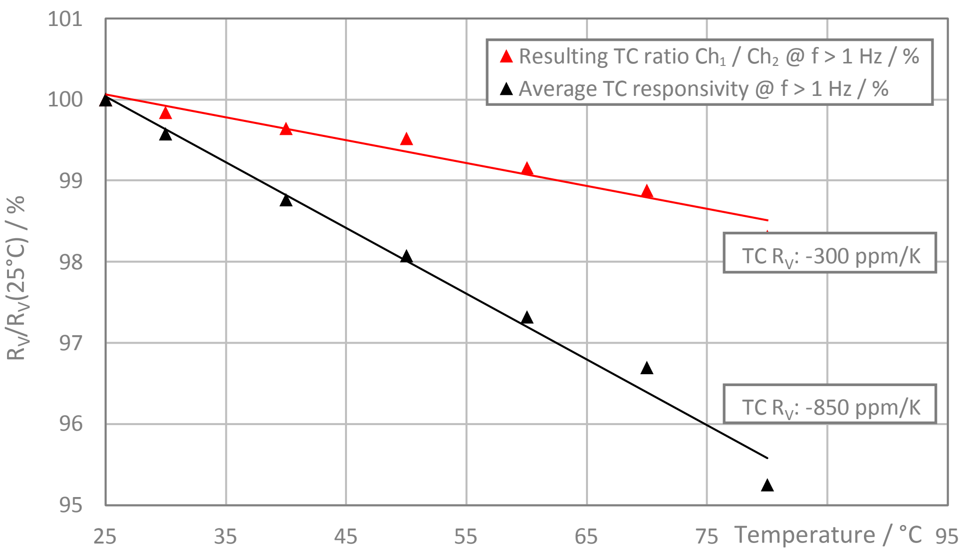


Figure 25: Temperature coefficients of a dual channel voltage mode detector LIM-222-GH

A common method for reducing the influences of ageing and contamination of the optical path is to use a reference channel and form quotients of the signals of both channels. Thus, the temperature coefficient of the overall configuration can also be reduced since only the difference between the temperature coefficients of both channels is effective here.

Figure 25 and Figure 26 illustrate how channels with similar temperature coefficients can be used to mutually offset each other. This method can be used both in voltage mode and in current mode.

Temperature Behaviour and Temperature Compensation

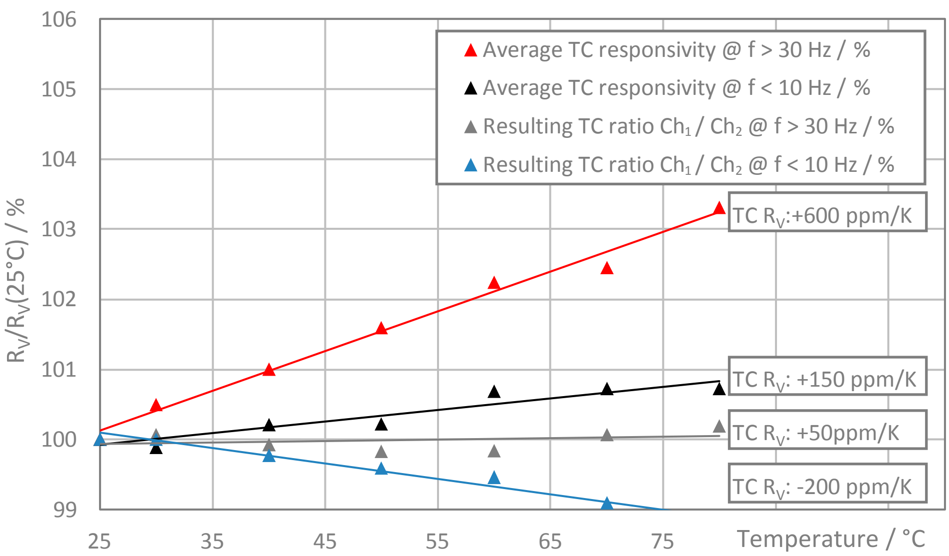


Figure 26: Temperature coefficients of a dual channel current mode detector LIM-262-GH

All considerations and examinations presented here apply exclusively to the pyroelectric detector itself assuming that all other influencing factors are constant and independent of the detector. During the development of a measurement system, however, the developer must consider and evaluate the sometimes complex interactions between the detector and other external components. External components such as infrared sources, optical path, heat capacity of holders and supports can have a substantial impact on the temperature behaviour of the entire system.

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