Temperature Behavior

1 Introduction

This application note is offered to provide some insight into how temperature affects the various components of a typical pyroelectric detector and how the effects of ambient temperature variations on detector performance can be minimized.

Pyroelectric detectors can be used over a wide ambient temperature range without cooling or stabilizing.
The active elements react to changes of incoming radiation levels. This effect is used to create an electrical detector signal.
Changes of ambient temperature will cause drift of the detector signal and noise expressed by the temperature coefficient (TC), because the components used within a detector change their properties with temperature.
Also fluctuations or instability in detector output can be caused by temperature changes especially in temperature ramps. To minimize such instabilities thermal compensation of the sensitive pyroelectric element is a very effective means of prevention.
Both effects should always be considered separately since they are caused by factors that require different corrective measures in detector design.

2 Temperature dependent Components within the Pyroelectric Detector

Figure 1 shows the basic commercial single element pyroelectric detector offered by InfraTec. In the figure there are the temperature dependent active and passive electrical and optical components indicated.

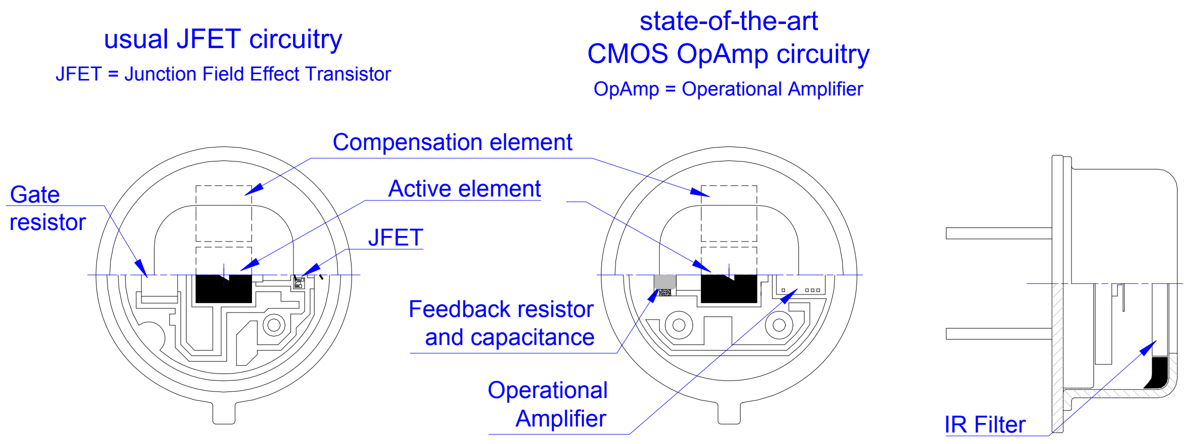


Fig 1: Typical InfraTec detector construction

The change of properties of the individual components results in a signal or noise density change of the complete detector represented by the Temperature Coefficient TC [ppm/K].

Temperature Behavior

2.1 Temperature dependence of the pyroelectric chip

By definition, the Curie point is that temperature above which the low-temperature pyroelectric polarized phase is transformed into a high-temperature non-pyroelectric unpolarized phase. The pyroelectric coefficient of these materials, which is a measure of eventual detector sensitivity, actually increases with increasing temperature up to the Curie point. In the case of Lithium Tantalate ($LiTaO_3$), from which almost all of InfraTec's pyroelectric detectors are made, the Curie temperature is 603 °C.

In most practical applications, where operating ambient temperatures are substantially lower (<+120 °C), the intrinsic temperature coefficient (TC) of the pyroelectric current is approximately +3500 ppm/K (+0.35 %/K). In a typical application, the active element of the pyroelectric detector is coated with an appropriate 'black' coating to enhance the infrared absorption of chopped or modulated incoming radiation, thus warming the pyroelectric crystal. Depending on the operating mode of the detector, the resulting current or voltage generated above the capacitance of the detector chip (typically 50 pF) is then converted into a useful signal. The electrical charges (current) generated even by minimal increases in crystal temperature are in the order of femto- to nanoamperes. It is important to note that an increase in detector case/package temperature can produce 'false' signals.

Electrostatic peaks of up to 150 V, for example, have been measured from highly insulated elements with case temperature increases as small as 10 °C.

2.2 Temperature dependence of integrated JFET and CMOS operation amplifier

The gate leakage current, as well as the input current noise of integrated Junction Field Effect Transistors (JFETs), increase substantially with increases in temperature. Particularly at higher temperatures, this increase is exponential. The gate leakage current of a typical FET is normally less than 1 pA at +25 °C, but can increase to well above 100 pA at +125 °C.
CMOS operational amplifiers (OpAmps) use an insulated input which enables an ultra low input bias current and low noise. The OpAmp circuitry is best suited at high temperatures up to +85 °C (see figure 2).

Another temperature effect can be created by the amplification drift of JFET or OpAmp. Increases in temperature will reduce the JFET common-source forward transconductance and increase the pinch-off voltage. Due to the high open-loop amplification and strong negative feedback of the OpAmps a drift of the OpAmp circuitry amplification determined by the temperature is not observed.

Temperature Behavior

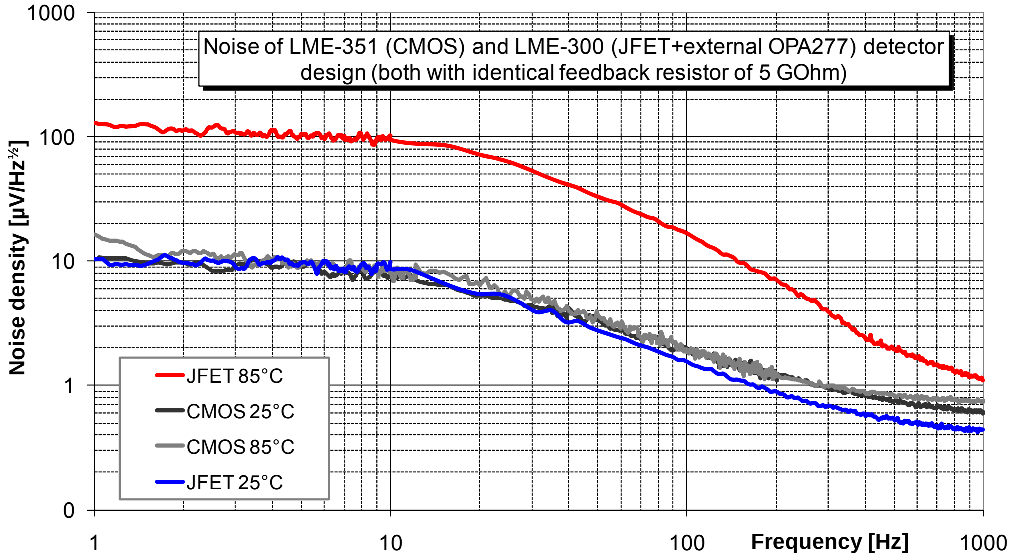


Fig 2: Different behavior of JFET and CMOS input transimpedance amplifiers at temperature increase

2.3 Temperature dependence of gate resistor as well as feedback components

High-Megohm resistors used as gate resistors in JFET circuitry or feedback resistors in OpAmp circuitry are characterized by high negative temperature coefficients (i.e. resistance decreases with increasing temperature). 100 GOhm resistors, that are routinely used with certain types of pyroelectric detectors, typically have TC's of about -2,000 ppm/K.

In voltage mode operation the change of the gate resistor resistance does not influence the output signal above the electrical cutoff frequency of about 30 mHz. The detector noise will however increase proportionally by $1/\sqrt{R}$).

In current mode operation the change of the feedback resistance value will influence both signal and noise.

NPO capacitors as well as printed parallel strip lines are used as feedback capacitors in OpAmp detectors and hence there is no measurable temperature influence on the detector parameters.

2.4 Temperature dependence of IR filters and windows

InfraTec pyroelectric detectors are coated with a black absorption coating whose spectral characteristics have been demonstrated not to be temperature dependent over the storage and operating temperature range. Please note that the maximum storage and operating temperature for detectors with metal black layer (applies only to LIE-312 and LIE-332 types) is only 60 °C. Above this temperature the high absorption foamy structure of the metal black layer will irreversibly sinter, which will cause a reduced absorption capability

The spectral transmittance of all windows and filters as part of the detector package varies with temperature.

For uncoated IR optical materials (e.g. CaF_2), temperature variation will mainly affect their transmittance and absorption edge (hence their useful range).

The spectral thermal shift and changes in transmission characteristics of coated filters, however, is determined by the materials and coating design used to manufacture such filters, and therefore vary by the type of filter (e.g. narrow band pass – NBP, wide band pass – WBP), wavelength region and filter manufacturer.

Temperature Behavior

Depending on customer requirements InfraTec uses IR filters manufactured with a low TC design (typical temperature shift approx. 0.25 nm/K, typical angle shift @ 15° approx. -27 nm, see figure 3) or a low angular shift design (typical temperature shift approx. 0.40 nm/K, typical angle shift @ 15° approx. -15 nm, see figure 4). All integrated narrow bandpass filters in InfraTec pyroelectric detectors for the 3 to 5 micron region have been chosen for their stability in design and are typically deposited on silicon substrates.

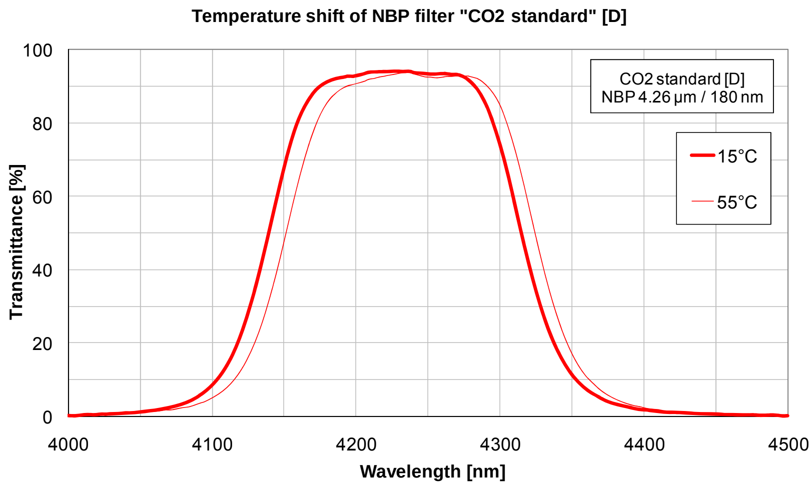


Fig 3: Temperature shift of NBP filter with low TC design

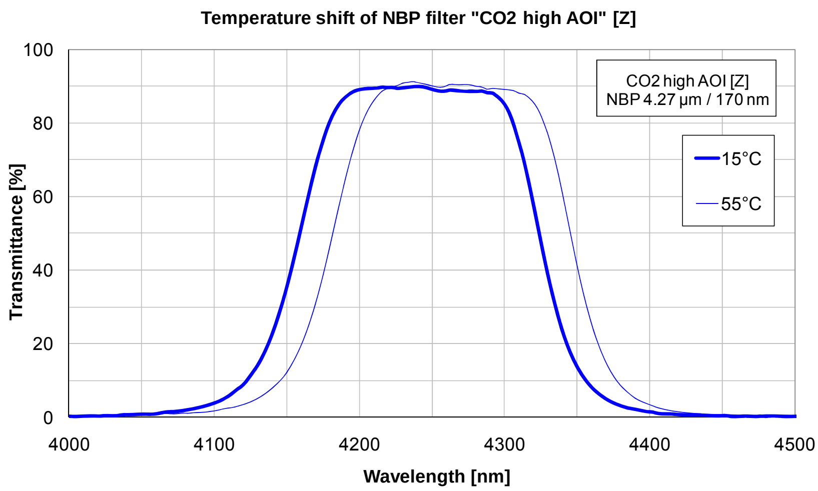


Fig 4: Temperature shift of NBP filter with low angular shift design

As a general rule, as temperature increases, IR bandpass filters will shift to longer wavelengths with some loss in transmittance. In contrast, with increasing angle the CWL will shift to shorter wavelengths in general.

Temperature Behavior

3 The Effects of Temperature Variation on overall Detector Performance

3.1 Change of Responsivity with temperature

Standard applications never analyze the pyroelectric current from the active element itself but the signal voltage generated by the pyroelectric current (voltage responsivity). Therefore the resulting TC of the pyroelectric detector depends on the operating mode of the detector, either the element in the open-circuit-operation (voltage mode detectors, JFET circuitry) or in short circuit configuration (current mode detectors, OpAmp circuitry). Due to the electrothermal conversion the pyroelectric current is proportional to the quotient of the pyroelectric coefficient *p* and the volume specific heat capacitance c_P'. In current mode the voltage signal is generated by the pyroelectric current flowing through the feedback resistor. The TC of responsivity in current mode is therefore influenced by the TC of the pyroelectric coefficient, the TC of the volume specific heat and the feedback resistor. In voltage mode in most cases additionally the TC of the relative permittivity of the pyroelectric material has to be included.
As examples hereafter some experimental data from a simple set-up is included to demonstrate the importance of understanding how system parameters interact. The temperature behavior of responsivity is presented in the following figures (also applies to the signal voltage measured directly at the detector).

InfraTec pyroelectric detector signals are nearly linear with temperature over the whole operation temperature range. Please note that the compensation element in a thermally compensated detector does not contribute to the output signal, therefore the TC of responsivity applies for both thermally compensated and uncompensated detectors.

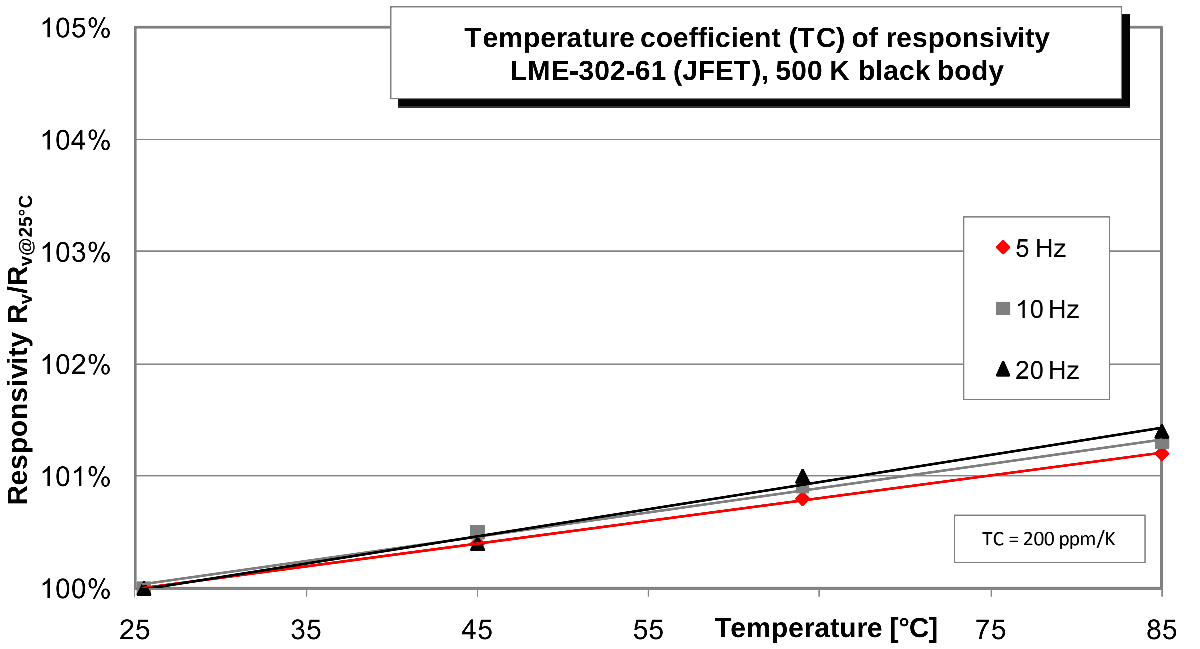


Fig 5: LME-302-61 (single channel; TO39 housing; medium chip size; low Micro; JFET; voltage mode; ch1: CaF2 0.7 mm thick)

Temperature Behavior

Detectors with JFET circuitry and without windows have typical TC´s in the range of (-1,000 ... 500) ppm/K, because the TC´s of the single components are almost compensated.

The temperature behavior of detectors with OpAmp circuitry depends significantly on the modulation frequency. Above the electrical cutoff frequency the resulting TC becomes more and more positive with a saturation at about 2,000 ppm/K. Below the electrical cutoff frequency the additional influence of the negative TC of the feedback resistor will decrease the TC of the responsivity.
The detector LME-335-61 has an electrical time constant of about 20 ms (100 GOhm // 0.2 pF). The electrical cutoff frequency is around 8 Hz. TC behavior changes around these limits as shown in figure 6.

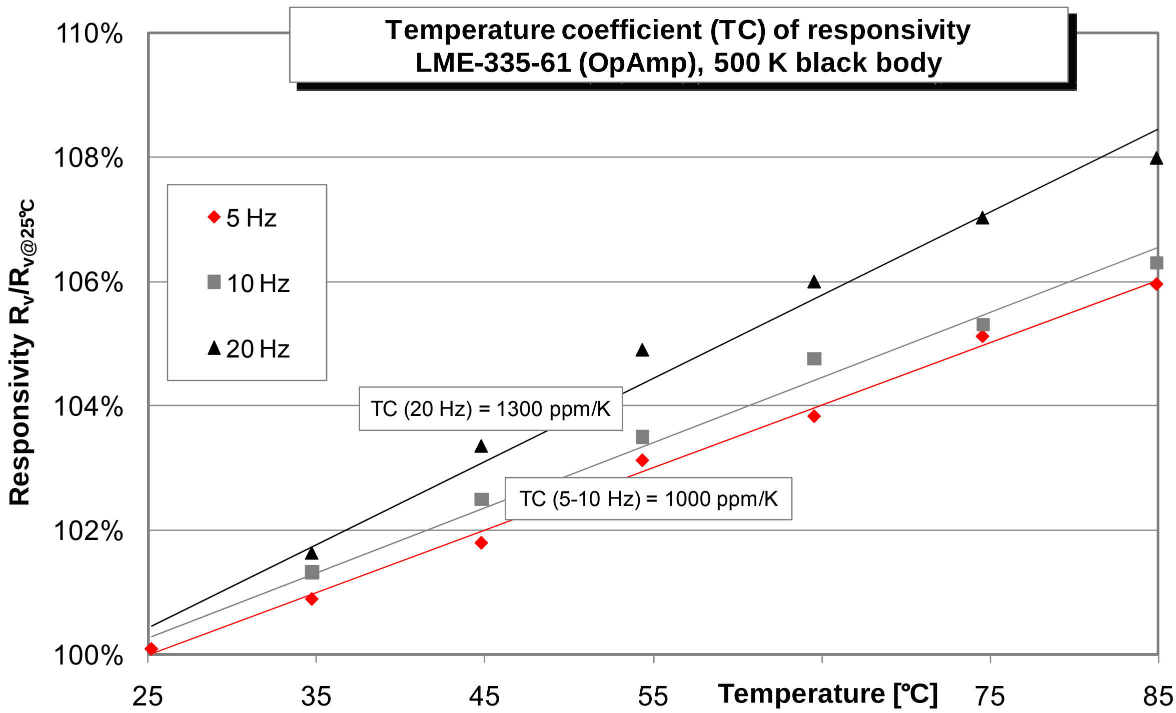


Fig 6: LME-335-61 (single channel; TO39 housing; medium chip size; thermal compensation; low Micro; OpAmp; current mode; feedback 100 GOhm; ch1: CaF2 0.7 mm thick)

Typical values for OpAmp detectors (with different filters or crystal windows and different feedback resistors) for different modulation frequencies are in the range of (-500 … +2,000) ppm/K.
Additionally, measurements with dual channel detectors and NBP filters were carried out. In a dual channel configuration with measurement and reference channel temperature influence can be reduced by using the quotient of both detector signals.

Temperature Behavior

For a typical voltage mode detector LIM-222-GH with NBP filters the following results were received:

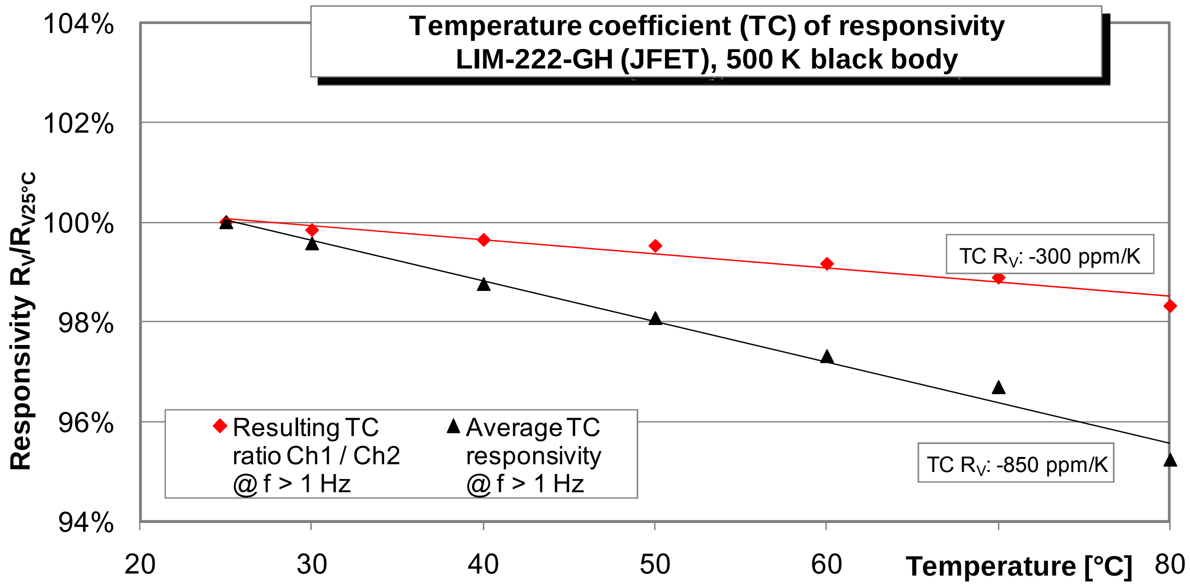


Fig 7: Dual channel detector LIM-222-GH (TO39 housing; small chip size; thermal compensation; JFET; voltage mode; ch1: NBP 3.40 µm/120 nm HC; ch2: NBP 3.95 µm/90 nm Ref.)

It illustrates a configuration which generates a slightly negative resulting average TC of -300 ppm/K (channel 1 = -1,000 ppm/K, channel 2 = -700 ppm/K).
Applying the ratio between the signal of the gas channel (channel 1) and the reference channel (channel 2) the impact of aging and pollution in the optical path can be compensated (red curve). According to the Theory of Errors the resulting TC emerges from the ratio for TC_{ch1} - TC_{ch2} (in figure 7 (-1,000 ppm/K) - (-700 ppm/K) = -300 ppm/K). In principle, positive and negative values can emerge for the resulting TC through this ratio.

The CMOS OpAmp equipped LIM-262-GH has been tested under the same arrangement and conditions as LIM-222-GH. The current mode detector's typically positive TC of responsivity was measured. The TC for this individual detector is in the range of (+100 ... +600) ppm/K, depending on the modulation frequency. Again in this case, the resulting TC is calculated from the Channel 1/Channel 2 ratio as a difference of TC_{ch1} - TC_{ch2}. Depending on the TC value of the single channel, positive and negative values can emerge, based on the calculated difference.

Temperature Behavior

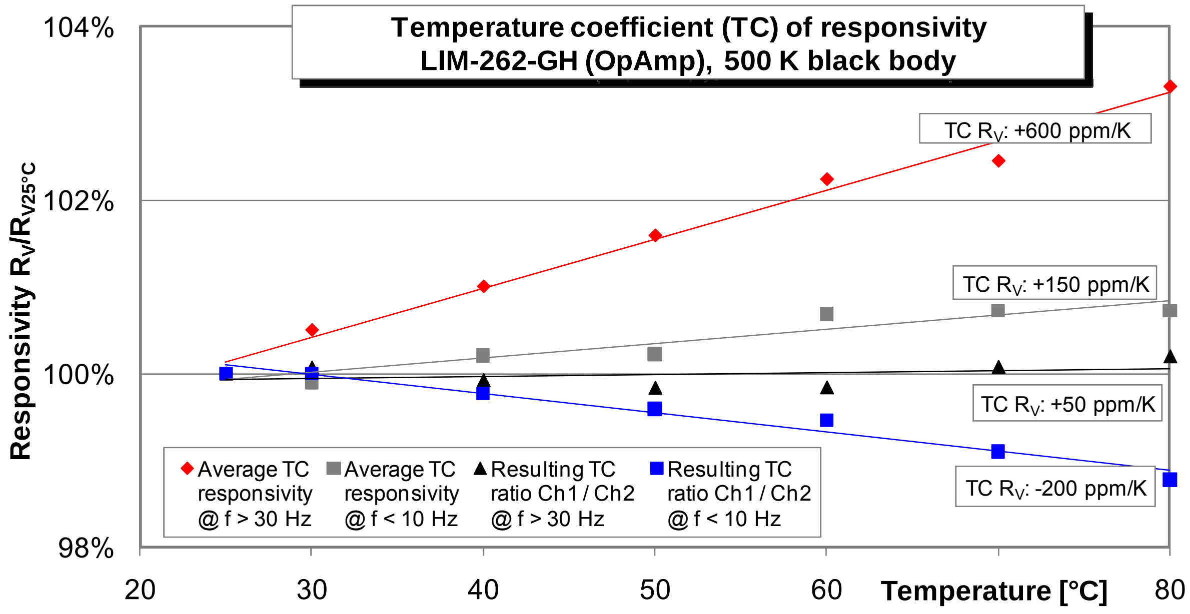


Fig 8: Dual channel detector LIM-262-GH (TO39 housing; small chip size; thermal compensation; OpAmp; current mode; feedback 100 GOhm; ch1: NBP 3.40 µm/120 nm HC; ch2: NBP 3.95 µm/90 nm Ref), identical filter placement as with the LIM-222-GH in figure 7.

3.2 Change of detector offset voltage with temperature in stable stage

Due to the increase in pinch-off voltage and gate leakage current, higher temperatures will always increase the offset voltage at the JFET circuitry because the negative TC of the gate resistor does not compensate this increase. Figure 9 shows the offset voltage vs. temperature of typical InfraTec detectors with JFET circuitry.

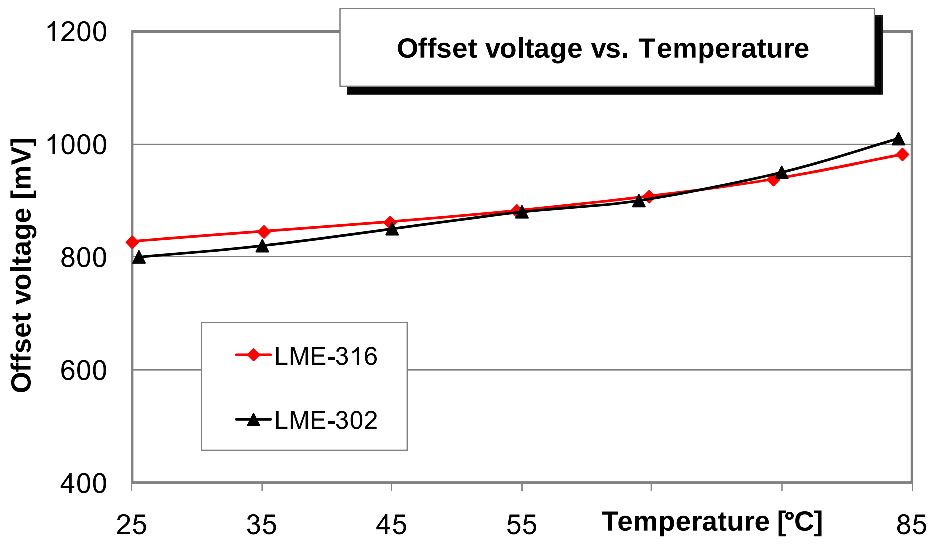


Fig 9: Offset voltage vs. temperature (JFET circuitry); after thermal transient period

Temperature Behavior

The DC offset voltage of the OpAmp circuitry is determined by the offset voltage of the OpAmp itself (typical in the range of max. ±5 mV) together with input bias current and feedback resistor. The bias current is about several pA at 85 °C. Figure 10 shows the offset voltage vs. temperature of typical InfraTec detectors with OpAmp circuitry.

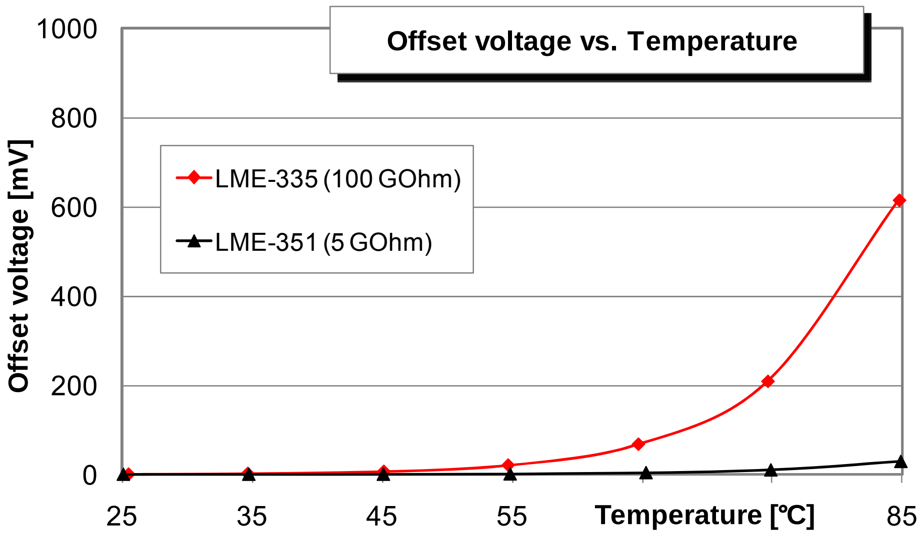


Fig 10: Offset voltage vs. temperature (OpAmp circuitry); after thermal transient period

Because the DC offset voltage is proportional to the product of input bias current and feedback resistance the increase at high temperatures is especially noticeable for detectors with large feedback resistors.

3.3 Change of Detector noise with temperature

An increase in gate leakage (JFET) or input bias (OpAmp) current together with the neg. TC of gate (JFET) or feedback (OpAmp) resistance value results in higher detector noise with increasing temperature.
This increase is particularly prominent at lower frequencies and for large resistance values (see figure 11 and 12).

Temperature Behavior

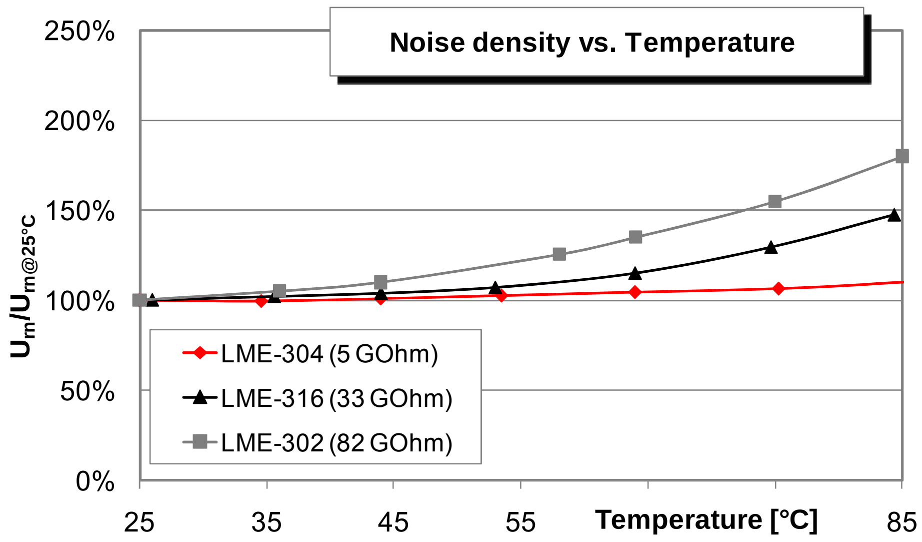


Fig 11: Noise density vs. temperature (voltage mode detectors with JFET)

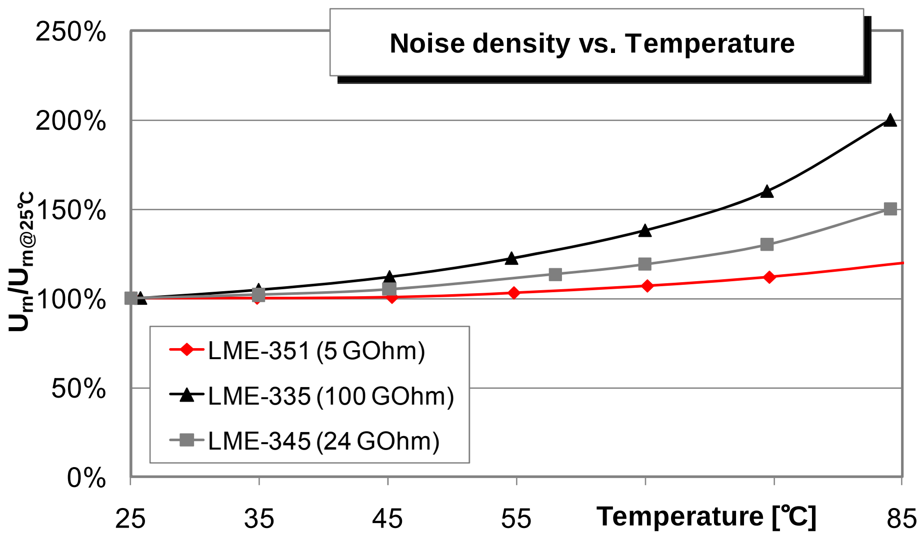


Fig 12: Noise density vs. temperature (current mode detectors with OpAmp)

Please note that all figures with measurement data show typical values, individual detectors may differ.
The drift of detector signal, offset voltage and noise which were shown above are independent from integrated temperature compensation elements. Those elements do not contribute to the actual detector signal, but only help to compensate for effects of thermal fluctuation for example in temperature ramps and hence increase stability.

Temperature Behavior

4 Variation of ambient temperature and temperature compensation

4.1 Offset voltage in temperature ramps

A change of the detector case temperature will usually generate a very low frequency signal, which can be of substantial magnitude. The commonly used voltage mode detectors with JFET circuitry are particularly susceptible to these temperature changes. Signals generated can cause unfavorable effects to a chosen preamplifier by pushing the limits of its operational range. The longer the thermal and electrical time constants of these detectors, the more sensitive they are to these changes. The state-of-the-art CMOS OpAmp detectors present in temperature ramps a DC offset adjustment in the same dimension as voltage mode detectors but the normal measurement AC signal is about 100-times higher. That means that the ratio DC offset adjustment to signal will be less than 1 % of the JFET circuitry and hence the dynamic range will not be limited anymore. Since thermal and electrical time constants are determined by detector construction, they can be reduced by design to attenuate, but not completely eliminate, the effects of case temperature changes in uncompensated detectors.

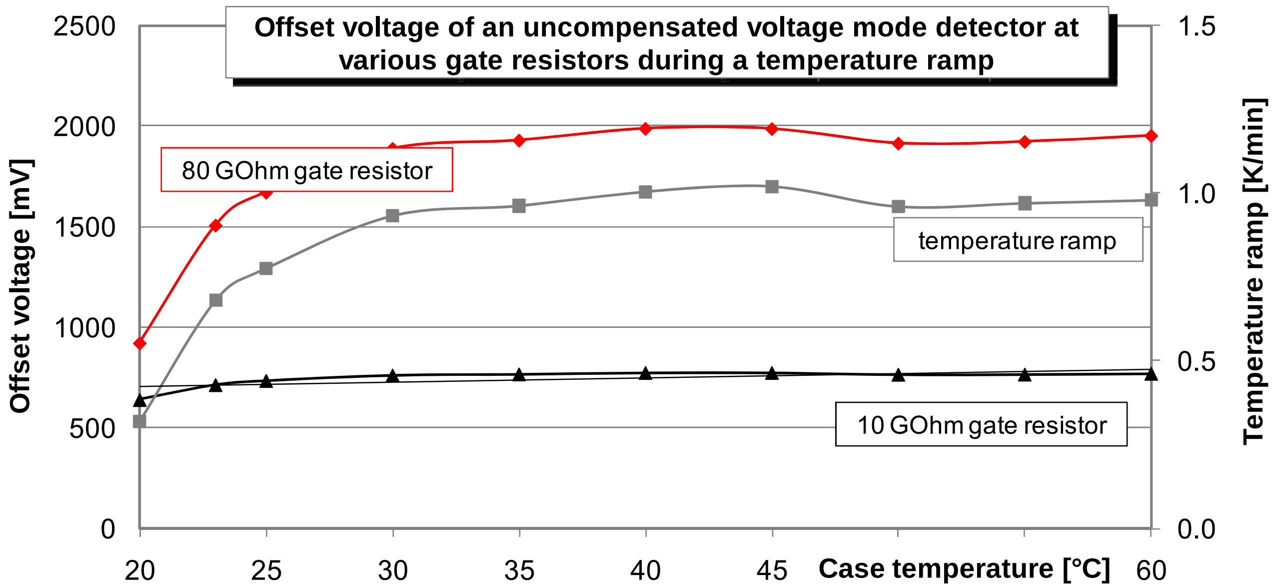


Fig 13: Offset voltage vs. temperature at various gate resistors (uncompensated voltage mode detector, JFET circuitry)

Figure 13 shows the typical effect of temperature variation on detector offset voltage for uncompensated voltage mode detectors with different gate resistors.
A decrease of the gate resistor substantially increases the detector stability. But on the other hand noise is inversely proportional to the square root of the gate resistance, e.g. a 9-times higher stability will cause a decrease of detector detectivity down to 33 %.
To overcome the problems associated with detector instability due to case temperature changes, an additional optically inactive (shielded) detector chip, known as the compensation element, can be added inside the detector package. The detector is then called a compensated detector. The compensation element has the opposite polarity of that of the active element. As case temperature varies, charges generated at the

Temperature Behavior

active and compensation element will essentially have the effect of canceling each other. Figure 14 shows the offset voltage vs. temperature of thermally compensated detectors, clearly presents the effectiveness of this arrangement.

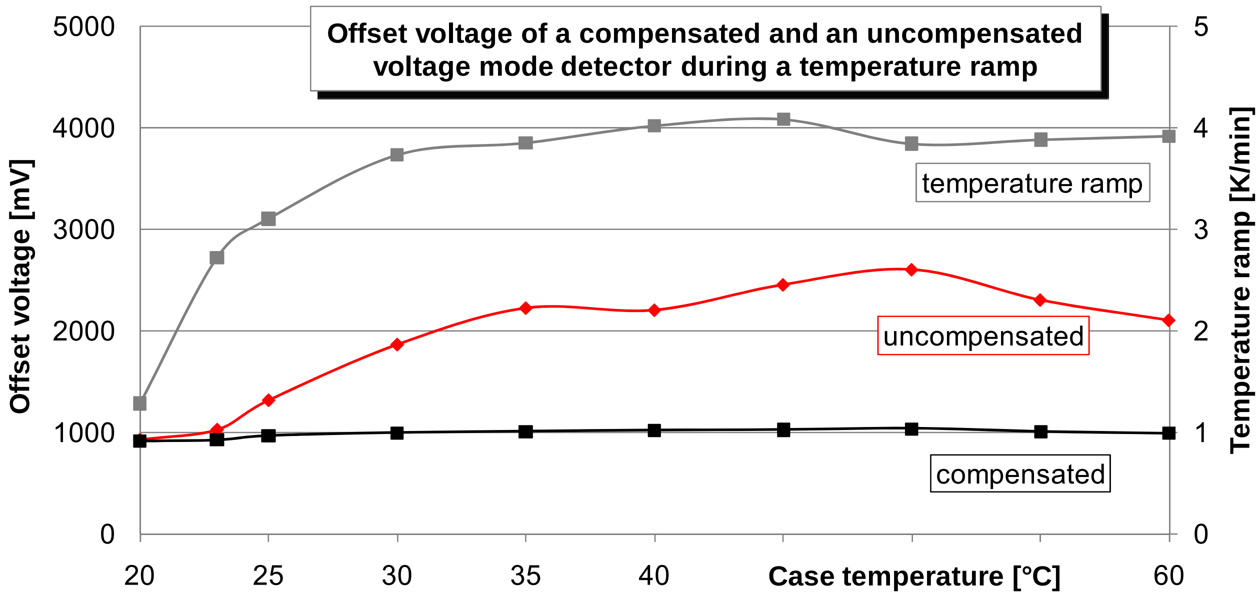
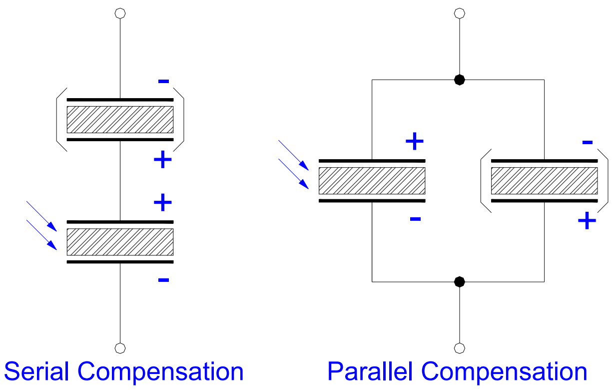


Fig 14: Offset voltage vs. temperature (compensated and uncompensated voltage mode detectors, JFET circuitry)

Thermally compensated pyroelectric detectors can be classified into two types: a) serial or b) parallel compensated, depending on the electrical connection of the active and the compensation element (see figure 15). The compensation element is always completely optically shielded from incoming IR radiation, hence although optically inactive but still an electrically effective capacitor. The influence of the compensation element regarding signal and detectivity is different between the common JFET circuitry and the state-of-the-art CMOS OpAmp circuitry.

The net effect of compensation for usual JFET circuitry is a reduction of detectivity to approximately 60 % for both compensation types, although signal and noise will be affected differently for each type. The approximate values of signal and noise for each type of compensated detector are shown as a percentage of those of an uncompensated detector in the figure above.
Due to the virtual short of compensation and pyroelectric element in the state-of-the-art OpAmp circuitry the parallel compensation neither causes signal nor detectivity losses.

Temperature Behavior



Serial Compensation
(Only with InfraTec's LIM-314)

- JFET circuitry: 100 % signal; 170 % noise
- OpAmp circuitry: not reasonable

Parallel Compensation
- JFET circuitry: 50 % signal; 70 % noise
- OpAmp circuitry: 100 % signal; 100 % noise

Fig 15: Serial and parallel compensation to increase the stability of the DC operating point of pyroelectric detectors in temperature ramps

The decision to use serial or parallel compensation for JFET voltage mode detectors should be based on the operating conditions from the detector. Parallel-compensated detectors are more stable at strong (more than 2 K/min) or long time constant temperature ramps (longer than 1 hour). Therefore most of InfraTec detectors are using parallel compensation. On the other hand the user may prefer the double signal of the serial-compensated voltage mode detector. We always recommend to test parallel compensation first.
In current mode detectors with integrated OpAmps the signal of compensated detector types is not changed due to the short circuit operation.
Due to that fact it is no longer necessary to compromise between signal magnitude and stability, only parallel compensation is applied for those current mode detectors.

4.2 Offset step response after fast temperature change

Often it is of interest to know how fast a detector can recover from an external temperature jump of the complete system.
In the following figures a typical reaction of the signal output by a fast increase of the ambient temperature from (25 … 40) °C which is transmitted to the detector housing is shown. The start of the jump reaction depends on the time which is needed to transfer the ambient temperature into the detector body.

In figure 16 typical curves for voltage mode detectors are shown. The offset jump of the uncompensated detector is very large and limited by the supply voltage. In comparison, the step response of the compensated detector is very small and the detector recovers much faster from the temperature jump. Please note that fabrication tolerances prevent an exact compensation and the step response could be either positive or negative. It is impressive to see the effect of thermal compensation realized by use of a second pyroelectric chip which is antiparallel-connected to the active chip in the detector.

Temperature Behavior

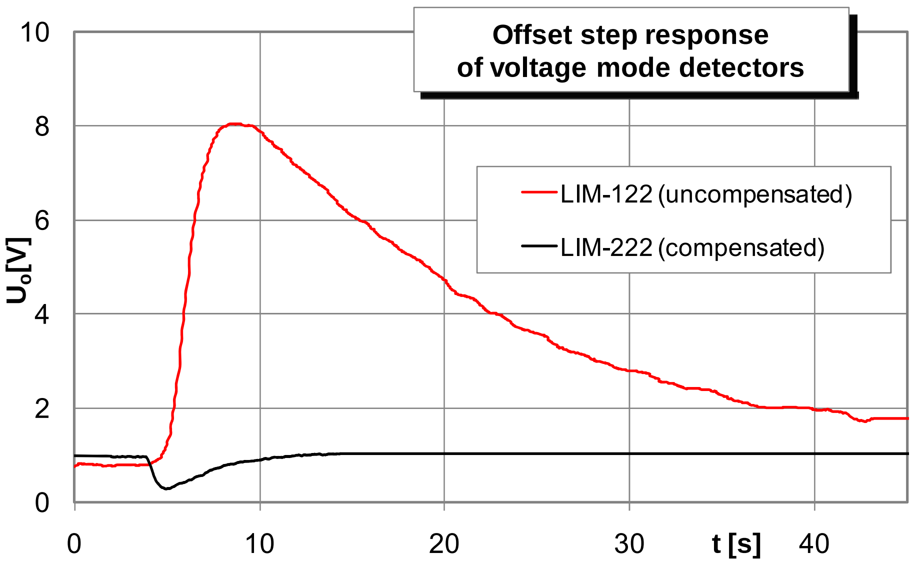


Fig 16: Change of offset voltage vs. time of typical voltage mode detectors after fast temperature increase

Similar reactions can also be noted for detectors in current mode. Figure 17 shows a typical step response of current mode detectors with integrated operational amplifier.

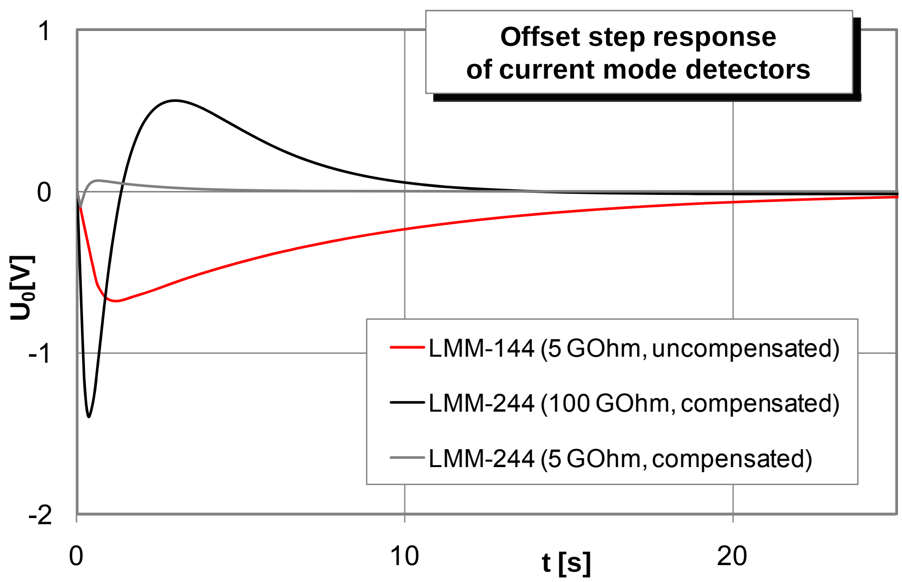


Fig 17: Change of offset voltage vs time of typical current mode detectors after fast temperature increase

It is also shown that for compensated detectors the step reaction can still further be minimized by use of a small feedback resistor with the disadvantage of a reduced detectivity.
Due to the much lower electrical time constant the recovery time of a detector in current mode with integrated OpAmp even with an uncompensated detector is much shorter compared to a compensated detector in voltage mode.

5 Summary

With this application note, InfraTec has attempted to provide IR system designers with some useful data regarding the effect of ambient temperature variation on pyroelectric detector performance due to the complex interaction of components as part of the detector assembly. As pyroelectric detectors are designed and incorporated into a specific application, designers must also consider how other system components (external to the detector) such as sources, optics etc. can alter the expected detector performance, too.
The signal conditioning method of the software used also will influence the result.