Pyroelectric Detectors General Characteristics

The radiation sensitive key components of InfraTec's detectors are single crystalline lithium tantalate ($LiTaO_3$) elements formed as a very thin plate capacitor. Lithium tantalate is a pyroelectric crystal whose ends become oppositely charged when heated. Although this unique effect was already known about in the ancient world and was given the name *pyroelectric* in 1824 by Brewster, even though the broad application in infrared detectors was introduced in the early 1970s. Nowadays due to its simple but robust construction and its performance the pyroelectric detector is one of the most widely-used thermal infrared detectors.

In fig. 1 the individual stages of the transformation from infrared radiation to an electrical signal is represented. Via a window or IR filter with a transmission rate of τ_F the radiation arrives at the pyroelectric element. The radiation flux Φ_S is absorbed and causes a change in temperature ΔT_P in the pyroelectric element. The thermal to electrical conversion is due to the pyroelectric effect by which the temperature change ΔT_P alters the charge density on the electrodes. An electrical conversion often follows in which, for example, an electrical signal is created by a preamplifier or impedance converter.

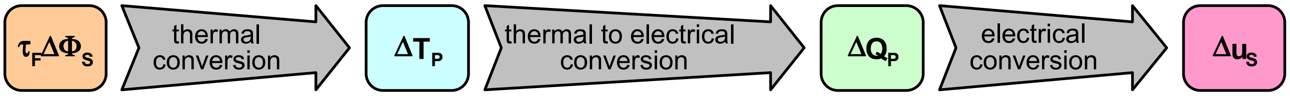


Fig. 1: Conversion stages of the pyroelectric infrared detectors

1. Thermal conversion

Within this chain thermal conversion is the basis for a high responsivity and a high signal to noise ratio, through which a high temperature change ΔT_P is the objective.

Fig. 2 represents a simplified thermal model and in fig. 3 the equivalent electrical circuit is depicted. The radiation sensitive element is characterised by the absorption rate α, the heat capacity H_P and the thermal conductance G_T to its surroundings which is represented by a heat sink with a given temperature T_A.

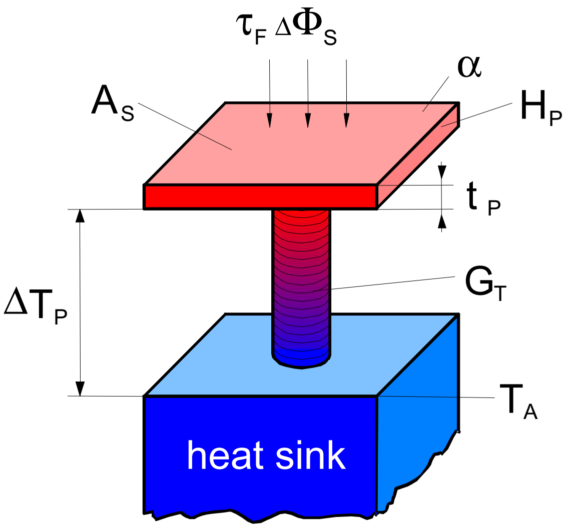


Fig. 2: Simplified thermal model

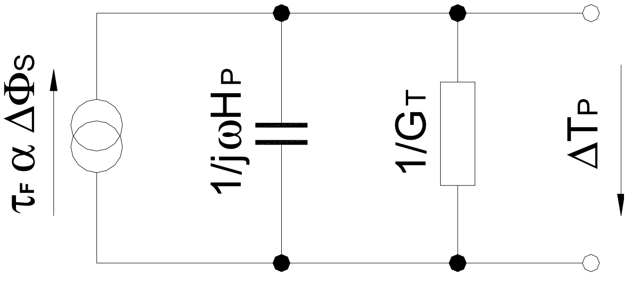


Fig. 3: Equivalent electrical circuit

Using the thermal time constant

$$\tau_T = \frac{H_P}{G_T} \tag{1}$$

the temperature difference results in

$$\Delta T_P = \frac{\alpha \tau_F \Phi_S}{\sqrt{{G_T}^2 + \omega {H_P}^2}} \tag{2}$$

or for sinusoidal agitation in the steady state

$$\Delta \tilde{T}_P = \frac{\alpha \tau_F \tilde{\Phi}_S}{G_T} \cdot \frac{1}{\sqrt{1 + (\omega \tau_T)^2}} \tag{3}$$

For significant temperature differences to occur the product **$\alpha\tau_F$** has to be as near to 100% as possible. This can especially be achieved by the use of an absorption layer. The heat capacity value **H_P** has to be low. For this the thickness **t_P** of the radiation-sensitive element has to be very low. Compromises are necessary as the required reduction in the thermal conductance **G_T** is opposed by the increase of the thermal time constant.

2. Thermal to electrical conversion

The thermal to electrical conversion is due to the pyroelectric effect and is proportional to the temperature rate and the detector‘s surface area:

$$i_P = pA_S \frac{\Delta T_P}{dt} \tag{4}$$

For sinusoidal agitation and considering equation (3) the result for the rms value of the pyroelectric short circuit current **i_P** is as follows:

$$\tilde{i}_P = \varpi p A_S \frac{\alpha \tau_F \tilde{\Phi}_S}{G_T} \cdot \frac{1}{\sqrt{1 + (\omega \tau_T)^2}} \tag{5}$$

Fig. 4 represents the frequency dependence on the temperature change and the short circuit current of a typical pyroelectric detector at an incident radiation flux of 1µW.

The frequency dependence on the temperature change portrays the typical low pass characteristics. The corner frequency **f_T** results from the thermal time constant according to equation (6)

$$f_T = \frac{1}{2\pi \tau_T} \tag{6}$$

and has the value of 1Hz. Below the corner frequency the temperature change attains a saturation value of 513µK. Above the corner frequency, the pyroelectric current, however, attains a saturation value of approximately 2.2pA.

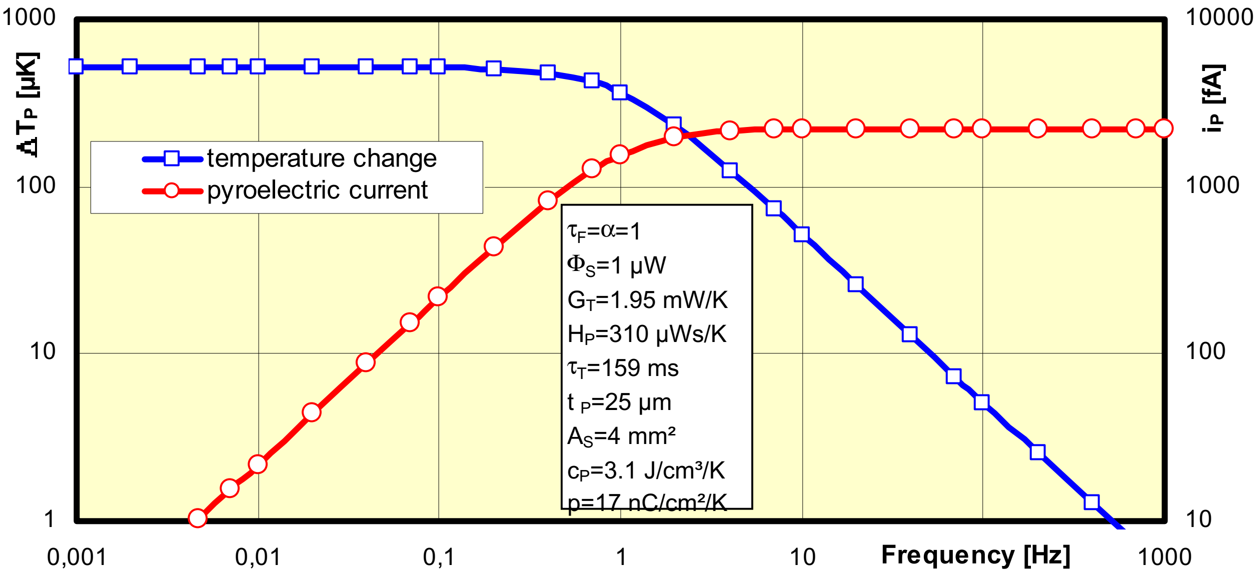


Fig. 4: Frequency dependence on temperature change and short circuit current of a pyroelectric element

3. Electrical conversion

3.1. Responsivity

This extremely low current, supplied by a high-impedance source has to be converted by a preamplifier with a high-impedance input. There are two alternatives available: voltage mode and current mode. The voltage mode can be implemented using a voltage follower and the current mode using an inverting operational amplifier as seen in fig. 5.

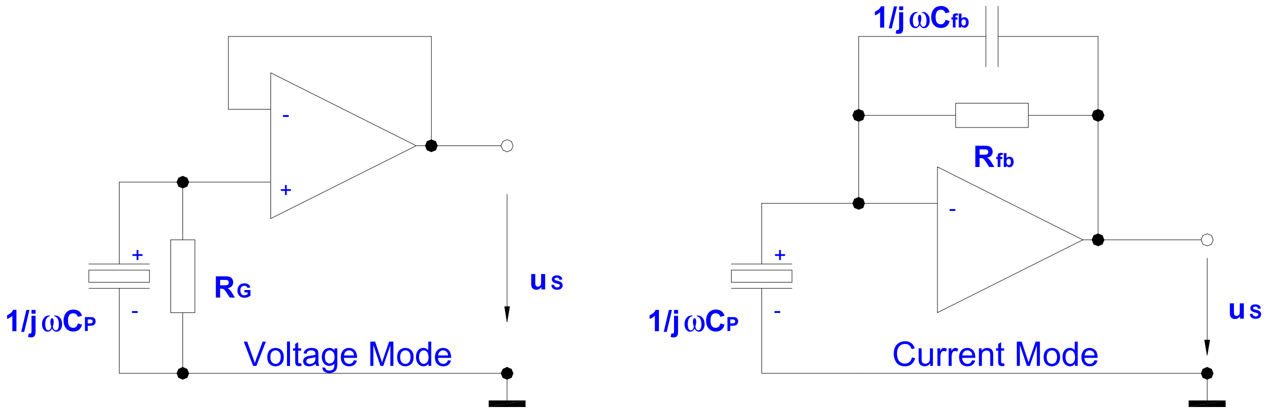


Fig. 5: Alternative preamplifier circuits

The signal voltage and the responsivity for both modes can be defined respectively using the same equation:

$$\tilde{u}_S = \varpi \alpha \tau_F \tilde{\Phi}_S A_S p \frac{1}{G_T} R \frac{1}{\left[1+(\varpi \tau_T)^2\right]^{1/2}} \frac{1}{\left[1+(\varpi \tau_E)^2\right]^{1/2}} \tag{7}$$

$$R_V = \frac{\tilde{u}_S}{\tilde{\Phi}_S} = \varpi \alpha \tau_F A_S p \frac{1}{G_T} R \frac{1}{\left[1+(\varpi \tau_T)^2\right]^{1/2}} \frac{1}{\left[1+(\varpi \tau_E)^2\right]^{1/2}} \tag{8}$$

where $R = R_G$, $\tau_E = R_G C_P$ is valid for the voltage mode (9)

and $R = R_{fb}$, $\tau_E = R_{fb} C_{fb}$ for the current mode. (10)

High megohm resistors may be necessary for both current and voltage mode to achieve a high signal voltage and responsivity but the feedback capacitance $\mathbf{C_{fb}}$ is kept considerably lower than the capacitance of the pyroelectric chip $\mathbf{C_P}$. Therefore the electrical time constant $\boldsymbol{\tau_E}$ is considerably lower for the current mode and the signal voltage above the electrical corner frequency is considerably higher than for the voltage mode. Fig. 6 illustrates the frequency dependence of both modes for typical detectors based on the results represented in fig. 4.

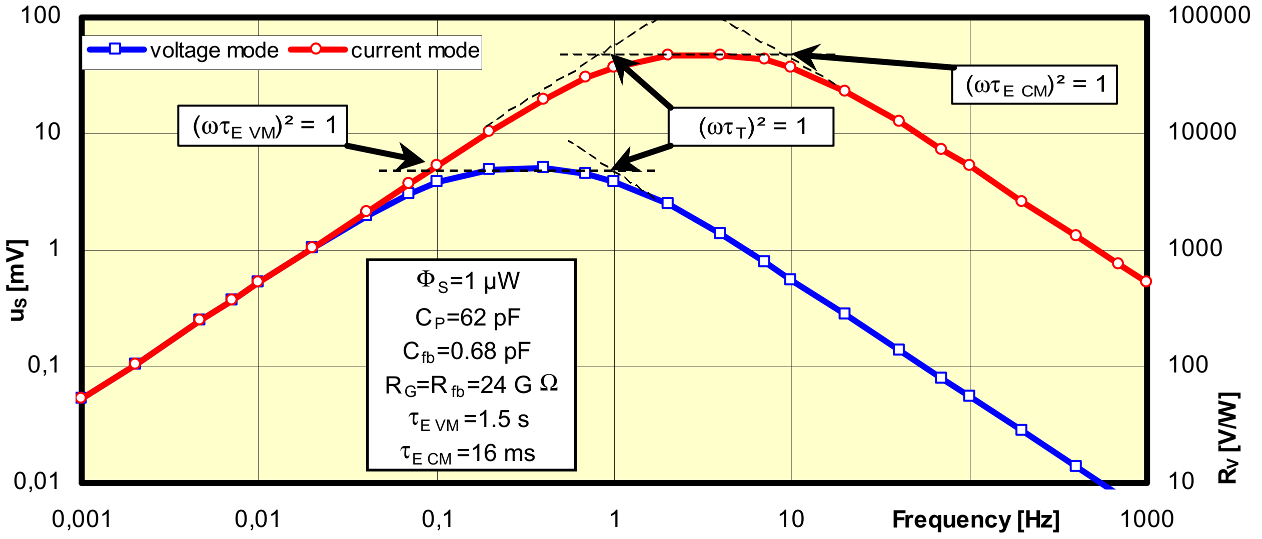


Fig. 6: Comparison of the frequency dependencies of signal voltage/ responsivity for voltage and current mode

3.2. Specific Detectivity

The noise sources of the pyroelectric chip and the preamplifier limit the detectable radiation flux or the signal to noise ratio. As a measure of the signal to noise ratio the specific detectivity is frequently used with the infrared detectors:

$$D^{*} = \frac{A_S^{1/2} S_V}{\tilde{u}_N} \tag{11}$$

where $\tilde{u}_N$ is the effective noise value which is related to a noise band width of 1Hz at the preamplifier output (voltage noise density). In table 1 the individual noise sources as well as the appendant specific detectivity components are summarised. The reciprocal quadratic superposition of the components results in the specific detectivity **D***. The frequency dependence and the resulting specific detectivity for a typical pyroelectric detector, with the already utilised parameters, is portrayed in fig. 7. It is irrelevant whether the detector is being used in the current or voltage mode as the same noise sources are operating in both cases.

noise sources	components of the specific detectivity *D**
temperature noise	$D_T^{*} = \alpha\tau_F \left(\frac{A_S}{4kT^2 G_T} \right)^{1/2}$
nyquist noise of the megohm resistor	$D_R^{*} = \alpha\tau_F \frac{p}{c'_P} \left(\frac{R}{4kT} \right)^{1/2} \frac{A_S^{1/2}}{t_P} \frac{\omega\tau_T}{\left[1+(\varpi\tau_T)^2\right]^{1/2}}$
tanδ noise of the pyroelectric element	$D_D^{*} = \alpha\tau_F \frac{p}{c'_P (\varepsilon_P \tan\delta_P)^{1/2}} \left(\frac{1}{4kT\varepsilon_0 \varpi t_P} \right)^{1/2} \frac{\omega\tau_T}{\left[1+(\varpi\tau_T)^2\right]^{1/2}}$
current noise of the preamplifier	$D_I^{*} = \alpha\tau_F \frac{p}{c'_P} \frac{1}{\tilde{i}_n} \frac{A_S^{1/2}}{t_P} \frac{\omega\tau_T}{\left[1+(\varpi\tau_T)^2\right]^{1/2}}$
voltage noise of the preamplifier	$D_U^{*} = \alpha\tau_F \frac{p}{c'_P} \frac{R'}{\left[1+(\varpi C'R')^2\right]^{1/2}} \frac{1}{\tilde{e}_n} \frac{A_S^{1/2}}{t_P} \frac{\omega\tau_T}{\left[1+(\varpi\tau_T)^2\right]^{1/2}}$ $current\ mode:$ $C' = C_P + C_I + C_{fb}$ $R' = R_P // R_I // R_{fb}$ $voltage\ mode:$ $C' = C_P + C_I$ $R' = R_P // R_I // R_G$

Table 1: noise sources and the appendant specific detectivity

In an ideal pyroelectric detector the heat exchange due to radiation between the pyroelectric chip and its surroundings acts as the only unavoidable noise source. This so-called temperature noise determines the component **D*$_T$** respectively the **theoretically highest possible specific detectivity** of a pyroelectric detector operated at room temperature:

$$D_{\max}^{*} = 1.8 \cdot 10^{10}\, cm \sqrt{Hz} / W \tag{12}$$

In a typical pyroelectric detector the other noise sources are considerably higher. Whilst the components **D*$_I$** and **D*$_R$** are dominant at low frequencies, the specific detectivity is considerably influenced by **D*$_U$** at high frequencies. At a medial frequency range **D*$_D$** is dominant.

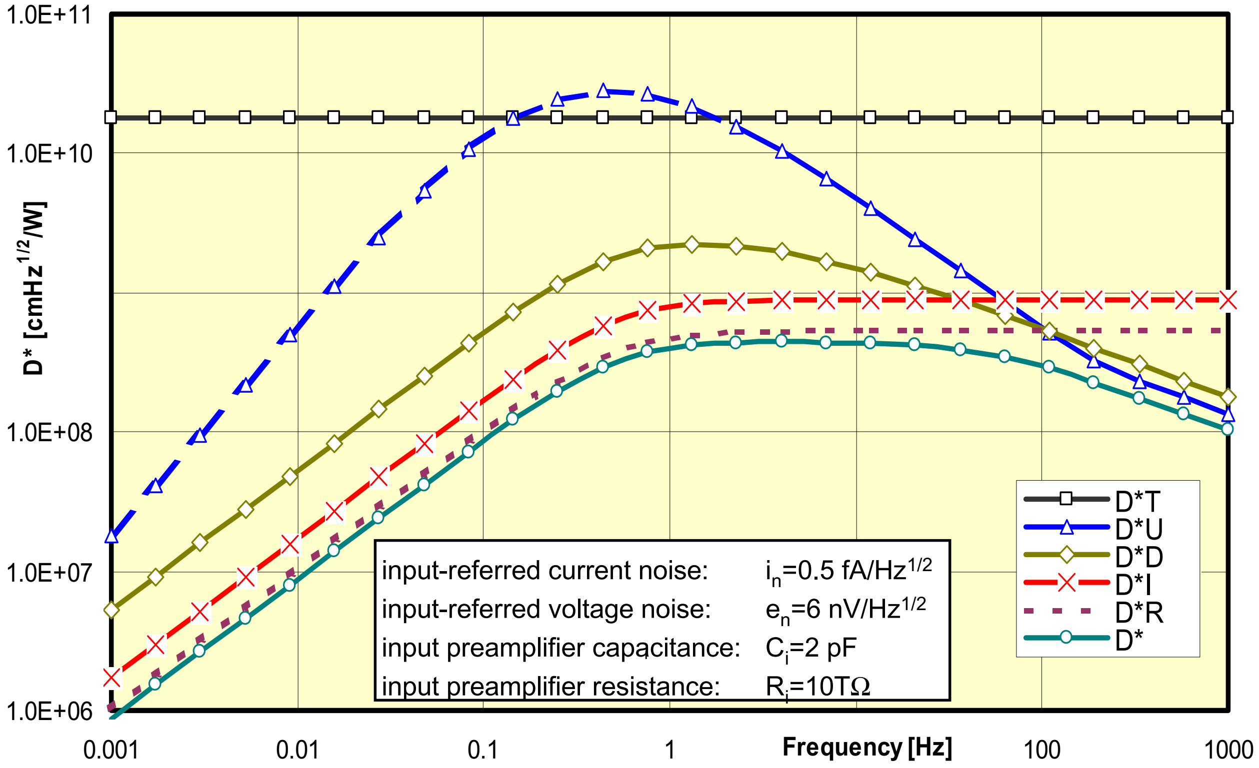


Fig. 7: Frequency response of the various components and the resulting specific detectivity of a typical pyroelectric detector

4. Voltage mode

4.1. General information

Due to its simplicity the voltage mode is the most commonly used operating mode for pyroelectric detectors. The following restrictions have to be considered regarding the layout of the amplifier and signal conditioning unit:

- The signal voltage of a pyroelectric voltage mode detector usually includes very low-frequency parts (mHz) caused by 1/f characteristics.

  The cut-on frequency of the amplifier‘s high pass should not be too low.

- The gate resistor (load resistor) should have a resistance of at least 10 GΩ for high performance.

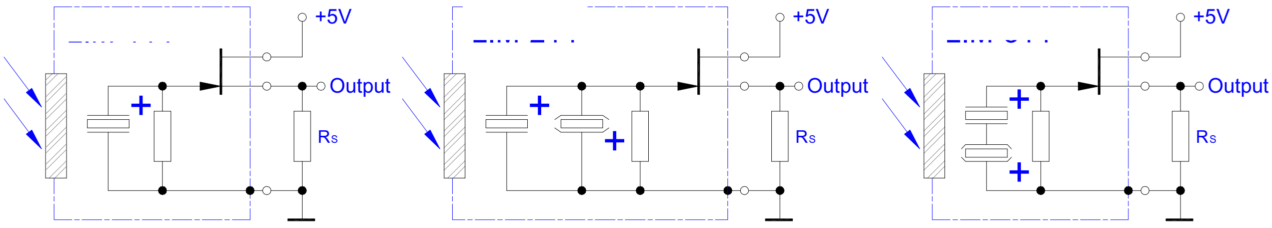
  The best solution for the protection of high impedance components against humidity, which would cause current leakage, is the integration of these inside transistor style housing. Pyroelectric detectors should not be used without integrated impedance preamplifiers in high performance applications.

- The output signal of voltage mode detectors corresponds to the time-integral of the IR radiation.

  This behaviour suppresses fluctuations effectively. Sinusoidal signals, however, are phase-shifted by 90° by this electrical lowpass filter ($f>f_T$).

4.2. Circuit diagram

In the simplest case the preamplifier is formed as a JFET source follower. The gate resistor and the JFET are integrated into the detector housing. The resistor in the source line is placed outside the detector housing (see fig. 8). The high signal to noise ratio and the low temperature dependence, as well as the simplicity of the circuitry, are the reason for this widespread use.



uncompensated parallel compensated serial compensated

Fig. 8: Basic circuits for the voltage mode

The gain for these circuits results from the transconductance of the JFET in the operating point and the source resistance:

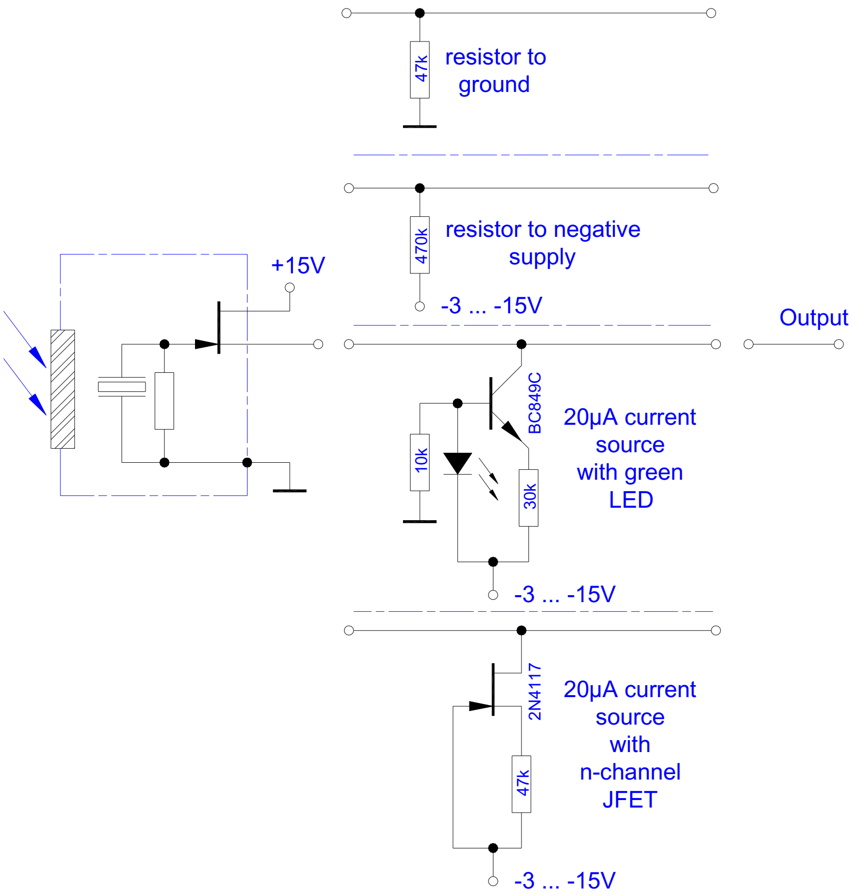
$$v \approx \frac{g_{fs} R_S}{1 + g_{fs} R_S} \leq 1 \tag{13}$$

The demand for a high source resistance or a small drain current can be deduced from this. See below for an example equation for a gain of at least 0.8 (**I_{DSS}** = saturation drain current):

$$\frac{I_D}{I_{DSS}} \leq 0.1 \tag{14}$$

However the demand for a low output resistance limits the increase of the source resistance necessary for a gain near to the value of 1. The source resistance should not be over 100kΩ at drain voltages up to 15 volts. A constant current source can be used as an alternative as this possesses a very high inner resistance. Next to a gain value of approximately 1 the temperature dependence of the transconductance is simultaneously suppressed and therefore the temperature stability of the gain is improved. See fig. 9 for suggestions concerning the operation of the source follower.

The JFET used by InfraTec represents a I_{DSS} with a characteristic value of 1mA. The recommended drain current values for the operation of the detectors are between 10 and 100µA.



	Remarks
1	• the simplest circuit • high drain current and gain dependency on operating point • low dynamic • asymmetrical tuning
2	• low current and and gain dependency as in (1) • a greater tuning range than in (1), symmetrical tuning possible • negative supply voltage
3	• higher dynamic inner resistance • greater tuning range than in (1), symmetrical tuning possible • negative supply voltage • lower temperature drift • 2 active and 2 passive components
4	• very high dynamic inner resistance • very low noise • greater tuning range than in (1), symmetrical tuning possible • negative supply voltage • greater temperature drift than in (3)

Fig. 9: Voltage mode detectors alternative circuitry for low-noise drain current supply

For the design of the drain current supply circuitry please note the following:

- The noise optimum for the JFET used in the InfraTec detector lies at 20µA.
- Pyroelectric detectors generate a DC offset in temperature ramps, which defines the large signal behaviour and can lead to significant changes in the gain of the source follower. Uncompensated standard detectors portray a positive offset shift. In comparison compensated detectors approximately portray a ten-fold lower shift, which, dependent on the symmetry between the active and the compensating element, can be positive or negative.
- This occurring effect, taking place exclusively in the temperature ramps, can be minimised at the expense of a higher noise, using a lower electrical time constant (available for all types on demand).
- The integrated current sources available, for example the LM 134 from NSC, worsen the signal to noise ratio or are expensive (REF200 from Burr-Brown / TI).

4.3. Wiring suggestions

The electronic components shown in figures 10 and 11 which are connected to the pyroelectric detector considerably determine noise and large-signal response. However, low cost OpAmps can be used due to the high signal level of pyroelectric detectors in comparison to thermopiles. The best results are achieved using low-noise amplifiers, which have been developed for high quality audio applications.

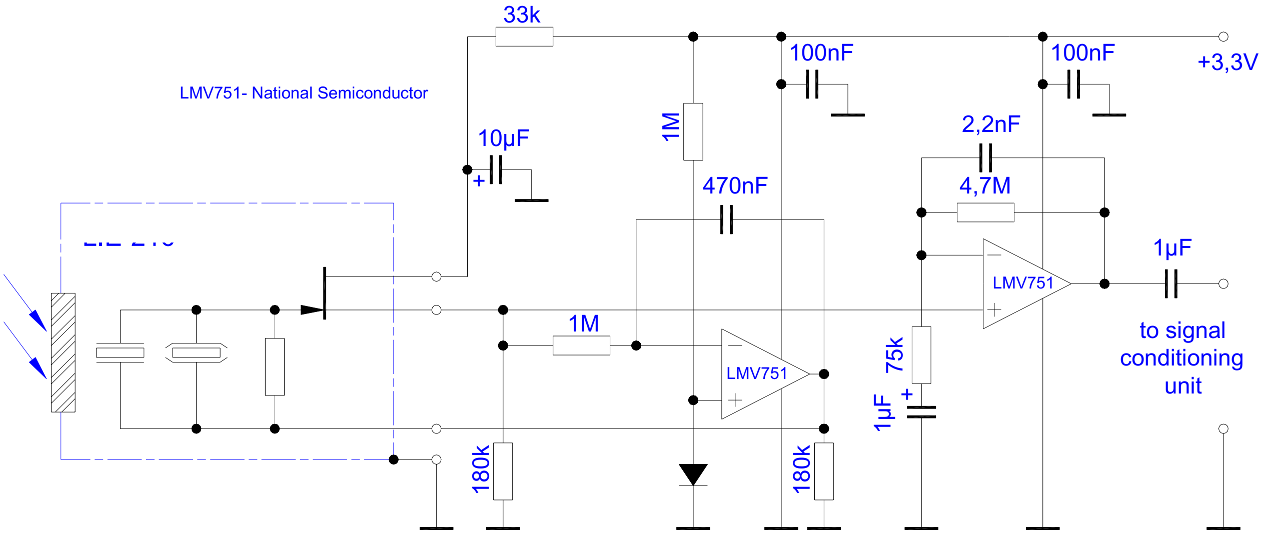


Fig. 10: Circuitry for a low voltage supply preamplifier for the NDIR gas analysing sensor (3,3V Lithium battery supply; 2 - 15Hz; gain of 60) using TO18 detectors with electrically isolated housing

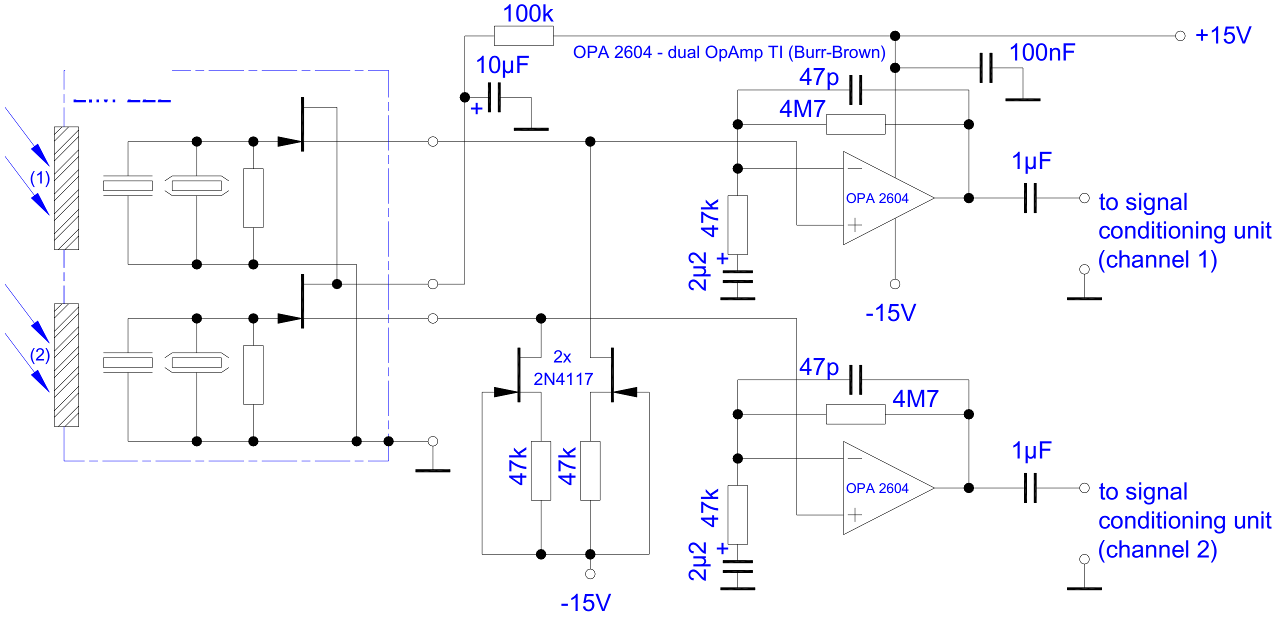


Fig. 11: Circuitry for a high precision preamplifier for the NDIR gas analysing sensor (± 15V bipolar supply; 5 - 200Hz; gain of 100) using dual colour detectors

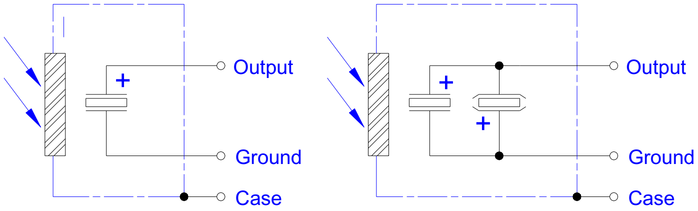
5. Current Mode

5.1. General information

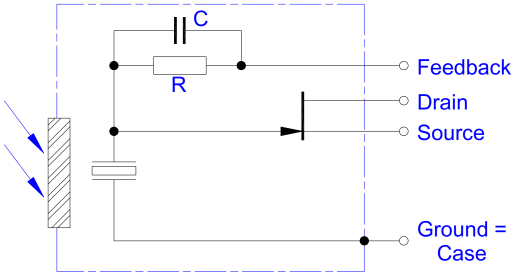
Current mode pyroelectric detectors are not as widely available as voltage mode ones, the most probable reason for this being that elementary pyroelectric detectors are mass produced for light switches and motion detectors. Due to the complexity of the preamplifier circuit its use was limited to very few applications. At InfraTec we can supply a wide spectrum of current mode detectors which makes it less complicated to include detectors for gas and fire detection.

5.2. Circuit diagram

- transistor style housing containing only the pyroelectric element (thermal compensation element also possible)



- TO housing containing the pyroelectric element (also with thermal compensation element), JFET and feedback resistor (an additional feedback capacitor of several picofarad is also possible). The integrated feedback–capacitor prevents so-called gain peaking.



- transistor style housing containing the pyroelectric element (incl. thermal compensation) and a complete current voltage converter with low input bias current OpAmp.

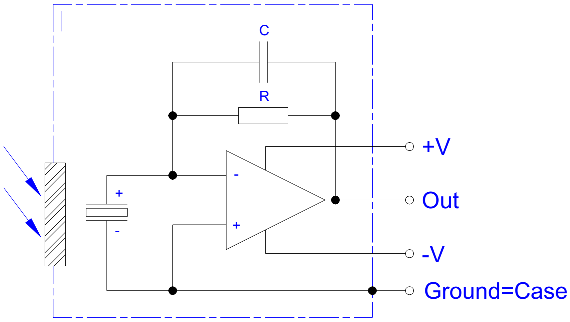


Fig. 12: Four alternative pyroelectric detectors suitable for current mode

5.3. Suggestions for wiring

The following examples are supposed to inspire one to consider the current mode as a reasonable alternative to the classic voltage mode based on the most modern available components.

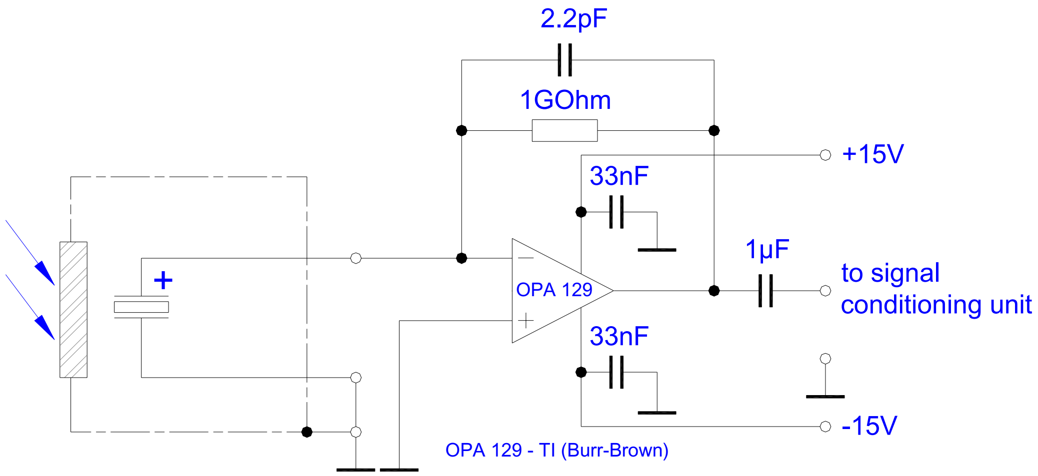


Fig. 13: Circuitry for current mode (0.2 - 25Hz; 1V/nA) of the pyroelectric detectors LME-301 and LME-501

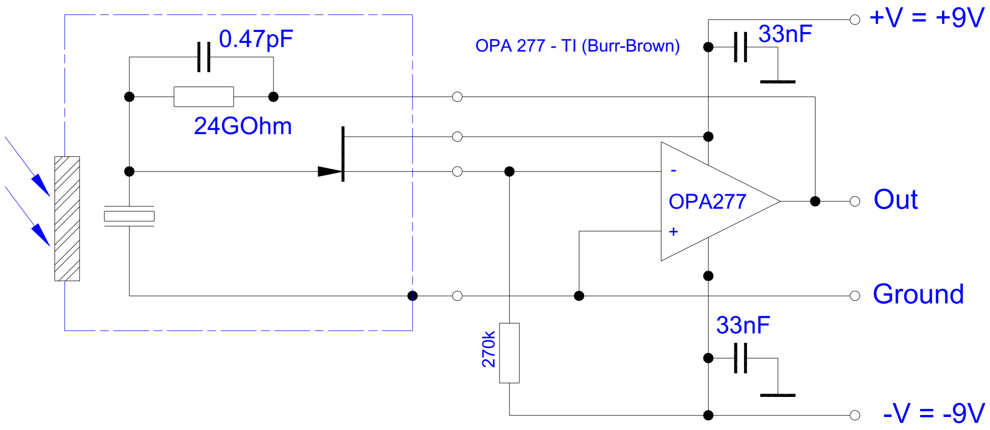


Fig. 14: Circuitry for current mode (typical 31,000 V/W) of the pyroelectric detectors LME-300 and LME-500

OpAmps with a low voltage noise should be used. Disadvantages of the circuitry depicted in figs. 13 and 14 include:

- EMC problems due to parasitic capacities
- permanent voltage offset across the pyroelectric element due to VGS of the JFET
- I_{GSS} of the JFET determines the level and temperature dependence of the current noise

These disadvantages can be avoided by integration of the OpAmp into the detector housing.

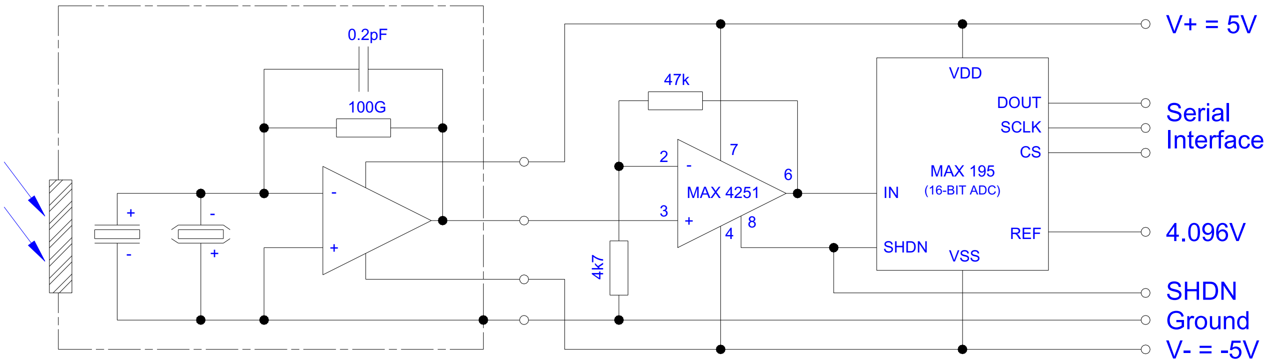


Fig. 15: Circuitry for single, dual or quad current mode detectors LME-235, LME-335, LIM-262, LMM-242 or LMM-244 directly coupled with an ADC

Modern low power OpAmps with low current and voltage noise ensure the same signal to noise ratio as in a simple JFET source follower, however due to the considerably lower electrical time constant it allows a considerably higher responsivity. The advantages of the integrated current mode detector are that:

- although there is a very high responsivity (R_V>100,000 V/W) there is also a high stability
- there is a very low output offset together with a very low offset temperature drift
- there is very low current noise together with a lower temperature drift of the specific detectivity at low frequencies (f<100Hz)
- there is a low electrical time constant and therefore a short warm-up phase and fast recovery time
- there is no signal loss when using the parallel compensation in thermal compensated detectors

Authors:
Mathias Heinze, PhD, InfraTec GmbH
Norbert Neumann, PhD, InfraTec GmbH