Detector Basics

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 in the ancient world and was given the name *pyroelectric* in 1824 by Brewster, 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 figure 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 τ_F the radiation arrives at the pyroelectric element. The radiation flux $\boldsymbol{\Phi_S}$ is absorbed and causes a change in temperature $\boldsymbol{\Delta T_P}$ in the pyroelectric element. The thermal to electrical conversion is due to the pyroelectric effect by which the temperature change $\boldsymbol{\Delta T_P}$ alters the charge density $\boldsymbol{\Delta Q_P}$ on the electrodes. An electrical conversion often follows in which, for example, an electrical signal $\boldsymbol{\Delta u_S}$ is created by a preamplifier or impedance converter.

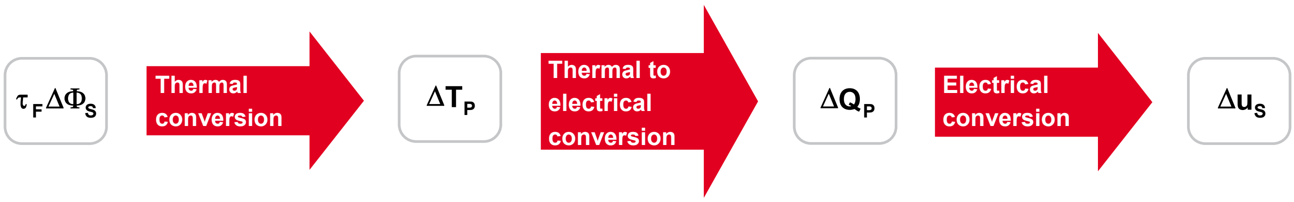


Fig 1: Conversion stages of the pyroelectric infrared detectors

1 Thermal Conversion

Within this chain thermal conversion is the basis for a high responsivity and a high signal-to-noise ratio (often abbreviated SNR or S/N), through which a high temperature change ΔT_P is the objective.
Figure 2 represents a simplified thermal model and in figure 3 the equivalent electrical circuit is depicted. The radiation sensitive element is characterized 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.

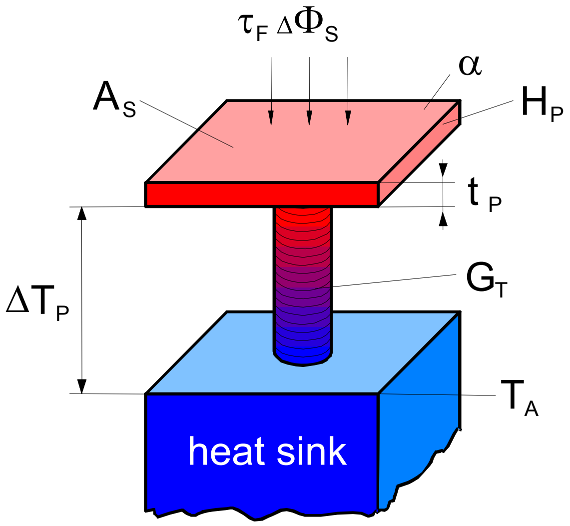


Fig 2: *Simplified thermal model*

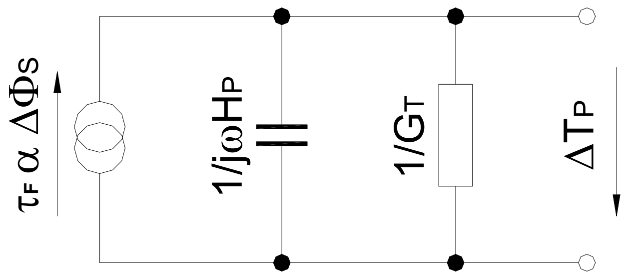


Fig 3: *Equivalent electrical circuit*

Using the thermal time constant
$$\tau_T = \frac{H_P}{G_T} \quad (1)$$

the temperature difference results in
$$\Delta T_P = \frac{\alpha \tau_F \Phi_S}{\sqrt{G_T^{\,2} + \omega H_P^{\,2}}} \quad (2)$$

or for sinusoidal agitation in the steady state
$$\Delta \tilde{T}_P = \frac{\alpha \tau_F \tilde{\Phi}_S}{G_T} \cdot \frac{1}{\sqrt{1+(\omega \tau_T)^2}} \quad (3)$$

For significant temperature differences to occur the product $\alpha\tau_F$ has to be as near as possible to 100 %. 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 τ_T. $\tilde{\Phi}_S$ is the effective sinusoidal radiation flux.

Detector Basics

2 Thermal to Electrical Conversion

The thermal to electrical conversion is due to the pyroelectric effect, described by the pyroelectric coefficient ***p***, and is proportional to the temperature rate ΔT_P and the detector's surface area A_S.

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

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

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

For the condition $(\omega\tau_T)^2 >> 1$

this equation changes to

$$\tilde{i}_P = \omega p A_S \frac{\alpha \tau_F \tilde{\Phi}_S}{G_T} \cdot \frac{1}{\omega\tau_T} = pA_S \frac{\alpha \tau_F \tilde{\Phi}_S}{H_P} = p \frac{\alpha \tau_F \tilde{\Phi}_S}{t_P c_P'} = \frac{p}{c_P'} \frac{1}{t_P} \alpha \tau_F \tilde{\Phi}_S \tag{6}$$

with c_p' being the volume specific heat capacitance.

Figure 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 1 µW. The frequency dependence on the temperature change shows the typical low pass characteristics. The corner frequency f_T results from the thermal time constant τ_T according to equation (7):

$$f_T = \frac{1}{2\pi\tau_T} \tag{7}$$

and has the value of 1 Hz. Below the corner frequency the temperature change attains a saturation value of 513 µK. Above the corner frequency, the pyroelectric current, however, attains a saturation value of approximately 2.2 pA according to equation (6).

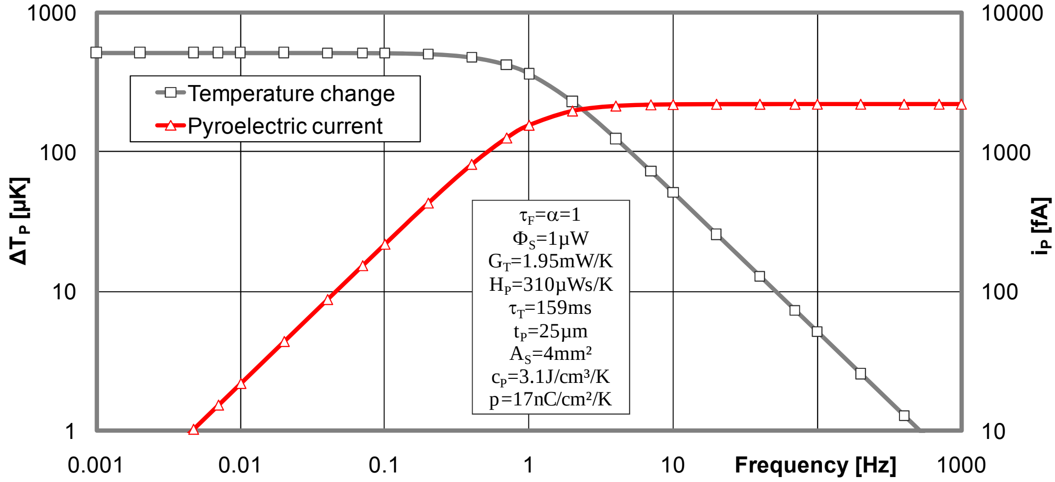


Fig 4: Frequency dependence on temperature change and short circuit current of a pyroelectric element

3 Electrical Conversion

3.1 Responsivity

The 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 a transimpedance amplifier (TIA) as seen in figure 5.

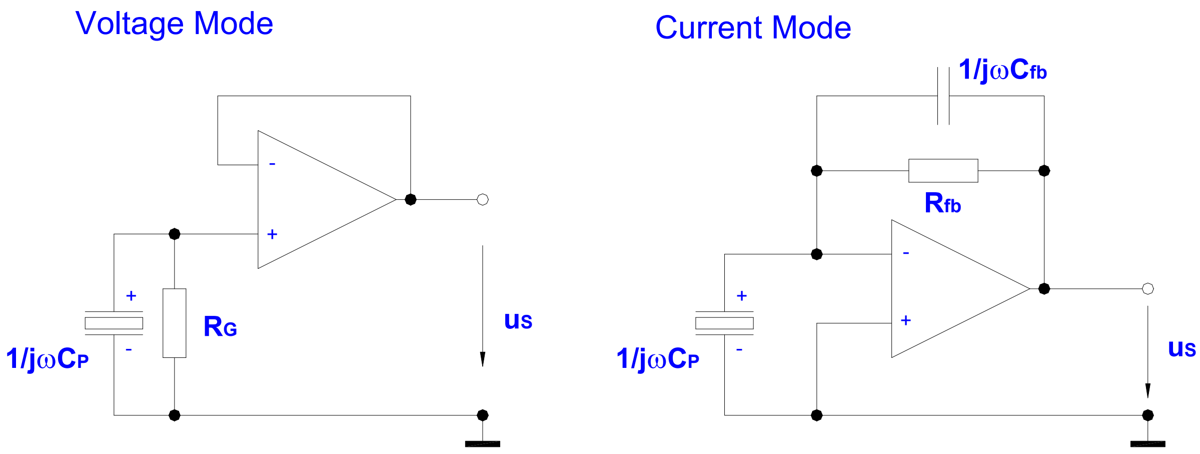


Fig 5: Alternative preamplifier circuits

The signal voltage $\boldsymbol{u_S}$ and the responsivity $\boldsymbol{R_V}$ for both modes can be defined respectively using the same equation:

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

$$R_V = \frac{\tilde{u}_S}{\tilde{\Phi}_S} = \varpi \alpha \tau_F A_S p \frac{1}{G_T} R \frac{1}{\left[1+(\varpi\tau_T)^2\right]^{1/2}} \frac{1}{\left[1+(\varpi\tau_E)^2\right]^{1/2}} \tag{9}$$

where $\begin{matrix} R = R_G \\ \tau_E = R_G C_P \end{matrix}$ is valid for the voltage mode (10)

and $\begin{matrix} R = R_{fb} \\ \tau_E = R_{fb} C_{fb} \end{matrix}$ for the current mode. (11)

In voltage mode (VM) this can be simplified as follows for the condition that $(\omega\tau_T)^2 >> 1$ and $(\omega\tau_E)^2 >> 1$

$$R_V = \alpha \tau_F \frac{p}{c_P{}'\varepsilon_p} \frac{1}{\varepsilon_0 \omega A_S} \tag{12}$$

Where $\boldsymbol{\varepsilon_0}$ is the dielectric constant and $\boldsymbol{\varepsilon_r}$ is the relative permittivity of the pyroelectric material.
In current mode (CM) there are two typical cases.

Detector Basics

For the first case that $(\omega\tau_T)^2 >> 1$ and $(\omega\tau_E)^2 >> 1$ is valid

Responsivity R_V results as follows:

$$R_V = \alpha\tau_F \frac{p}{c_P'}\frac{1}{t_P}\frac{1}{\omega \cdot C_{fb}} \tag{13}$$

If $(\omega\tau_T)^2 >> 1$ and $(\omega\tau_E)^2 << 1$
is valid the responsivity R_V is equal to:

$$R_V = \alpha\tau_F \frac{p}{c_P'}\frac{1}{t_P} \cdot R_{fb} \tag{14}$$

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

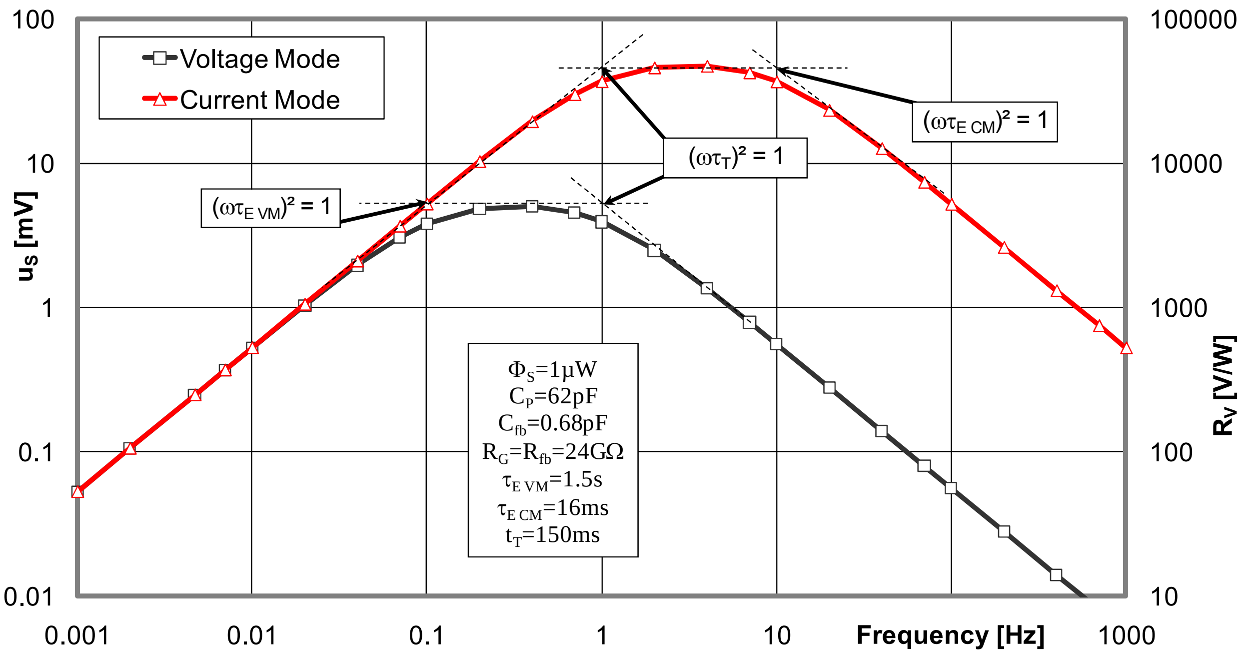


Fig 6: Comparison of the frequency dependencies of signal voltage/responsivity for voltage and current mode

3.2 Noise and specific detectivity

The noise sources of the pyroelectric chip limit the detectable radiation flux or the signal-to-noise ratio. Noise sources are:

- tanδ noise of the pyroelectric element
- Temperature noise
- Input noise voltage of the preamplifier
- Input noise current of the preamplifier
- Johnson noise of the high-megohm resistor

As a measure of the signal-to-noise ratio the specific detectivity is frequently used in conjunction with infrared detectors:

$$D^* = \frac{A_S^{1/2} R_V}{\tilde{u}_N} \qquad (15)$$

Where $\tilde{u}_N$ is the effective noise value which is related to a noise bandwidth of 1 Hz at the preamplifier output (voltage noise density). In table 1 the individual noise sources as well as the appendant noise voltage components are summarized. The quadratic superposition of the components results in the noise voltage density $\tilde{u}_N$. The frequency dependence and the resulting noise voltage density for a typical pyroelectric detector LME-302, with the already utilized parameters, is portrayed in figure 7.

Noise sources	**Components of the noise density** $\tilde{u}_{NX}$	
tanδ noise of the pyroelectric element	$\tilde{u}_{ND} = (4kT\varpi C_P \tan\delta_P)^{1/2} \frac{R}{\left[1+(\omega\tau_E)^2\right]^{1/2}} A_V$	(16)
Temperature noise	$\tilde{u}_{NT} = \frac{R_V}{\alpha}(4kT^2 G_T)^{1/2}$	(17)
Voltage noise of the preamplifier	$\tilde{u}_{NV} = e_N A_V$	(18)
Current noise of the preamplifier	$\tilde{u}_{NI} = i_N \frac{R}{\left[1+(\omega\tau_E)^2\right]^{1/2}} A_V$	(19)
Johnson noise of the high-megohm resistor	$\tilde{u}_{NR} = \left(\frac{4kT}{R}\right)^{1/2} \frac{R}{\left[1+(\omega\tau_E)^2\right]^{1/2}} A_V$	(20)

Table 1: Five essential noise sources (A_V: voltage gain)

Detector Basics

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 temperature noise $\tilde{u}_{NT}$ determines the **theoretically highest possible specific detectivity** of a pyroelectric detector operated at room temperature:

$$D^*_{\max} = 1.8 \cdot 10^{10}\, cm\sqrt{Hz}/W \quad (21)$$

In a typical pyroelectric detector the other noise sources are considerably higher, shown in figure 7. The Johnson noise of the high-megohm resistor dominates at low frequencies (< 10 Hz). At medium frequencies (100 Hz), the tanδ noise of the pyroelectric element dominates the resultant noise density. At high frequencies (> 1,000 Hz), the voltage noise of the preamplifier specifies the resultant voltage noise density.

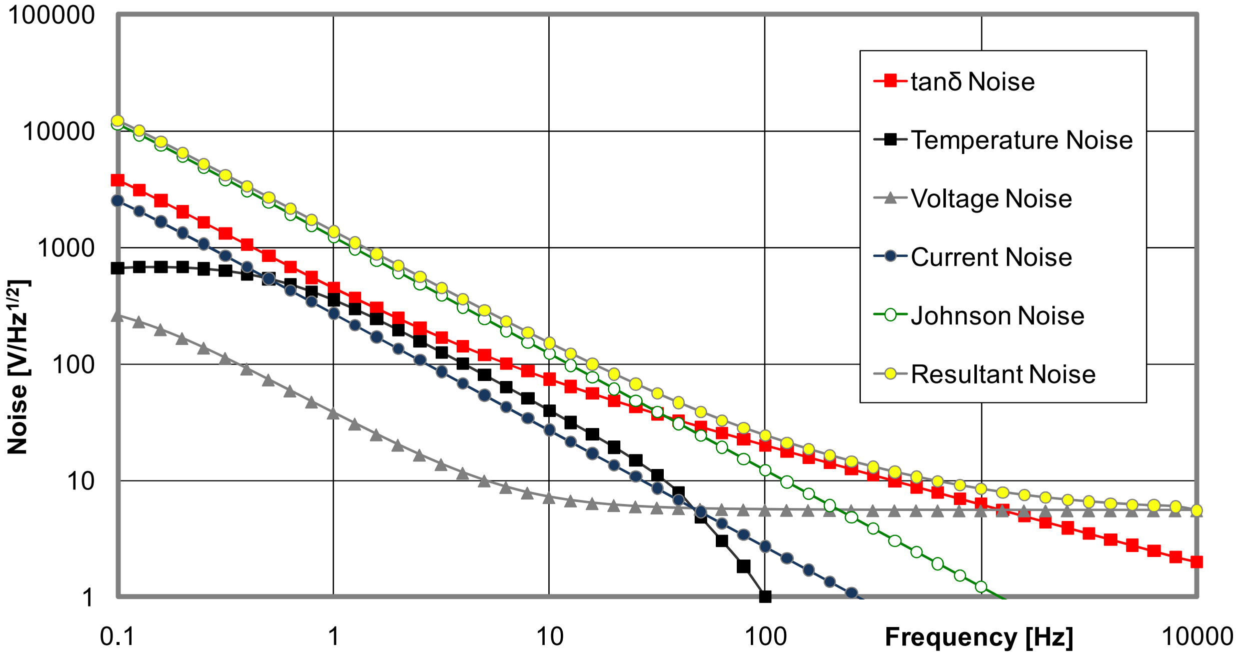


Fig 7: Frequency response of the resulting voltage noise density and of the various components of the voltage noise density of a typical pyroelectric detector (LME-302)

4 Voltage Mode

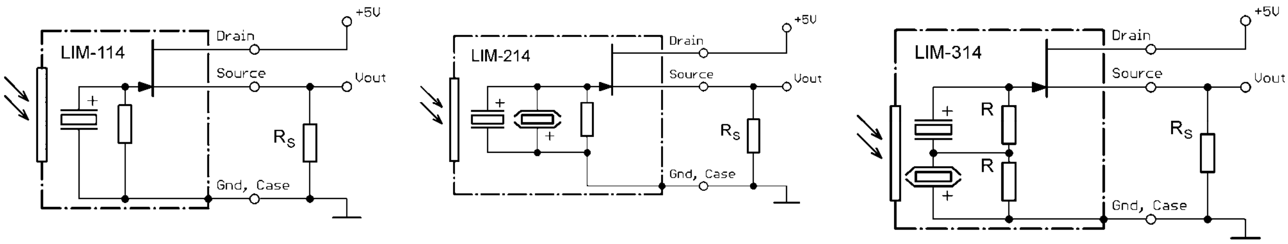
4.1 General information

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 GOhm 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 behavior 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 $\boldsymbol{R_S}$ in the source line is placed outside the detector housing (see figure 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.



Without thermal compensation Parallel compensation Serial compensation

Fig 8: Basic circuits for the voltage mode

The gain A_v for these circuits results from the transconductance $\boldsymbol{g_{fs}}$ of the JFET in the operating point and the source resistance $\boldsymbol{R_S}$:

$$A_v \approx \frac{g_{fs} R_S}{1 + g_{fs} R_S} \leq 1 \qquad (22)$$

The demand for a high source resistance or a small drain current can be deduced from this.

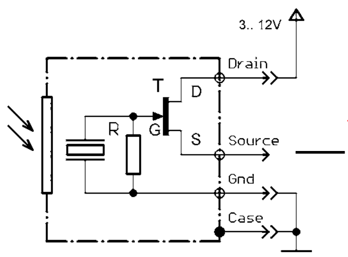
Detector Basics

See below for an example equation for a gain of at least 0.8 (**I_{DSS}** = saturation drain current):

$$\frac{I_D}{I_{DSS}} \leq 0.1 \qquad (23)$$

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 100 kOhm at drain voltages up to 15 V. 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 figure 9 for suggestions concerning the operation of the source follower.

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



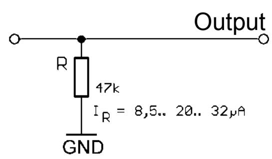
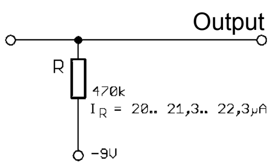
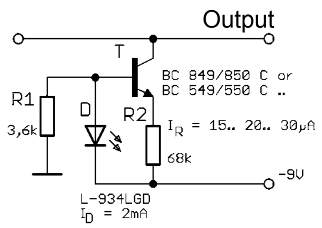
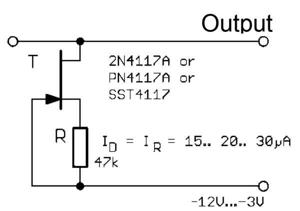
Circuit		Remarks
	(1)	■ The simplest circuit ■ High drain current and gain dependency on operating point ■ Low dynamic ■ Asymmetrical tuning
	(2)	■ Lower current and gain dependency on operating point as in (1) ■ A greater tuning range than in (1), symmetrical tuning possible ■ Negative supply voltage
	(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)	■ Higher dynamic inner resistance ■ Low noise ■ Greater tuning range than in (1), symmetrical tuning possible ■ Negative supply voltage ■ Greater temperature drift than in (1)

Fig 9: Alternative low-noise drain current supplies for voltage mode detectors

Detector Basics

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 20 µA.
- Pyroelectric detectors generate a DC offset in temperature ramps, which defines the large signal behavior 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 tenfold 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 minimized at the expense of a higher noise, using a lower electrical time constant (available for all types on demand).
- The available integrated current sources, 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 to 15 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 contrast to thermopiles. The best results are achieved using low-noise amplifiers, which have been developed for high quality audio applications.

Wiring for a low voltage supply preamplifier:

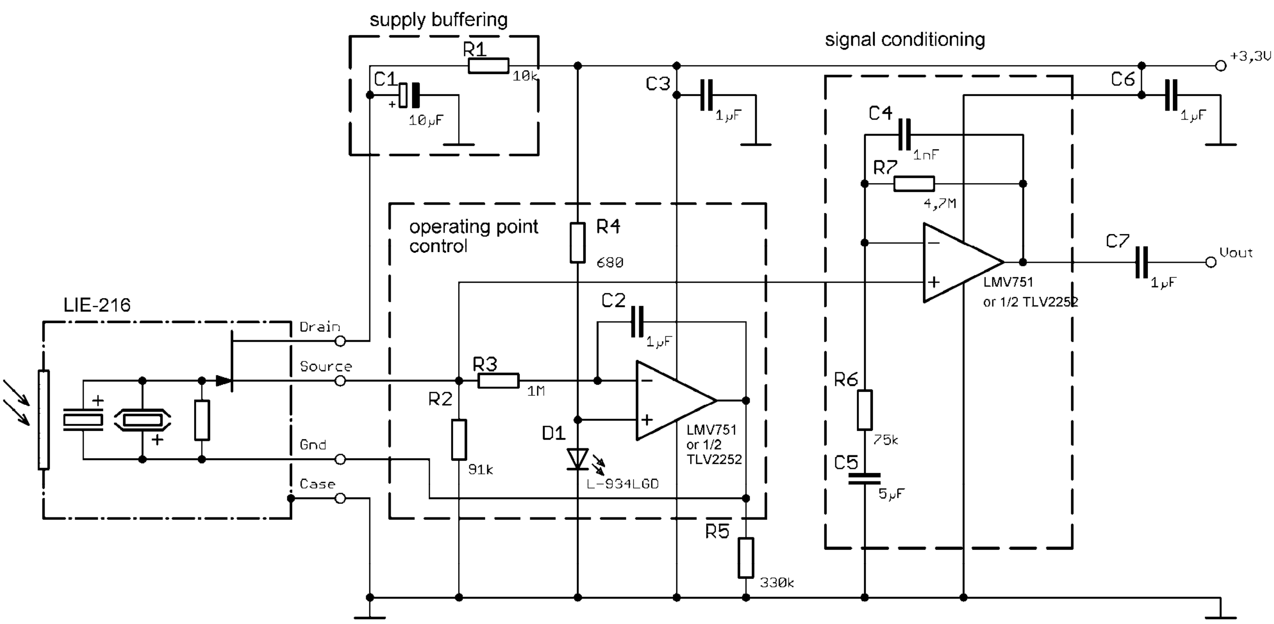


Fig 10: Using TO18 detectors with electrically isolated housing (3.3 V Lithium battery supply; (0.4 … 33) Hz; gain 60 dB)

Detector Basics

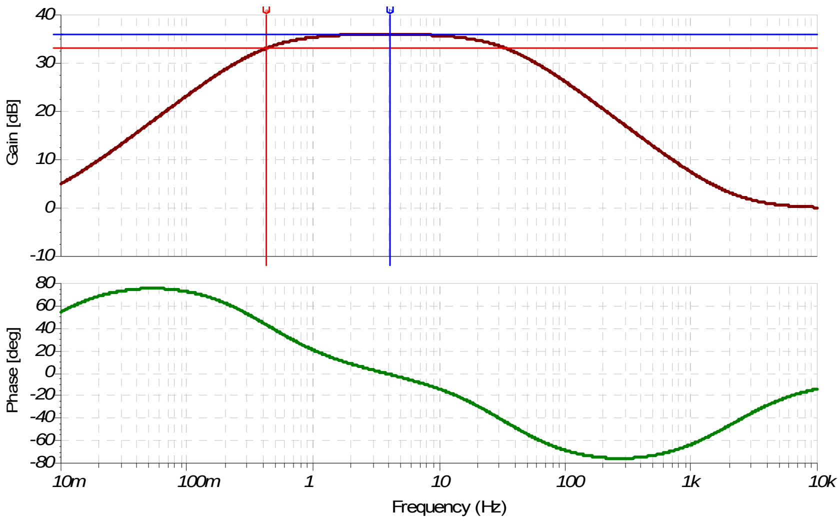


Fig 11: Gain and phase of preamplifier as per figure 10 vs. frequency

a) b) c)

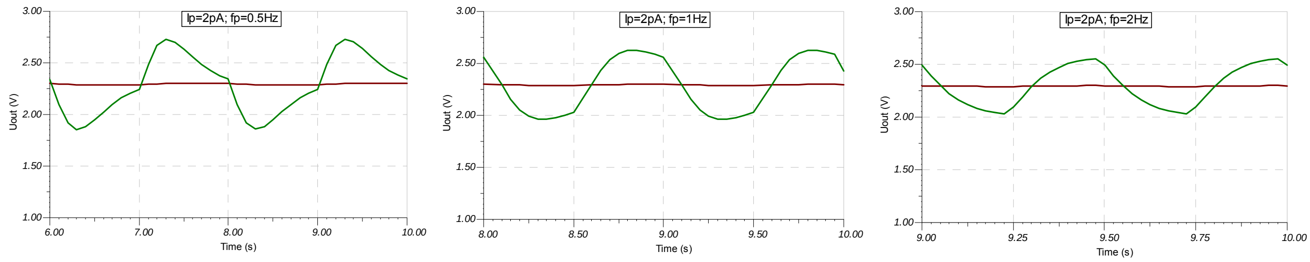


Fig 12: U_{out} of detector and preamplifier as per figure 10 at different frequencies

a) 0.5 Hz b) 1 Hz c) 2 Hz (simulated)

Wiring for a high precision preamplifier:

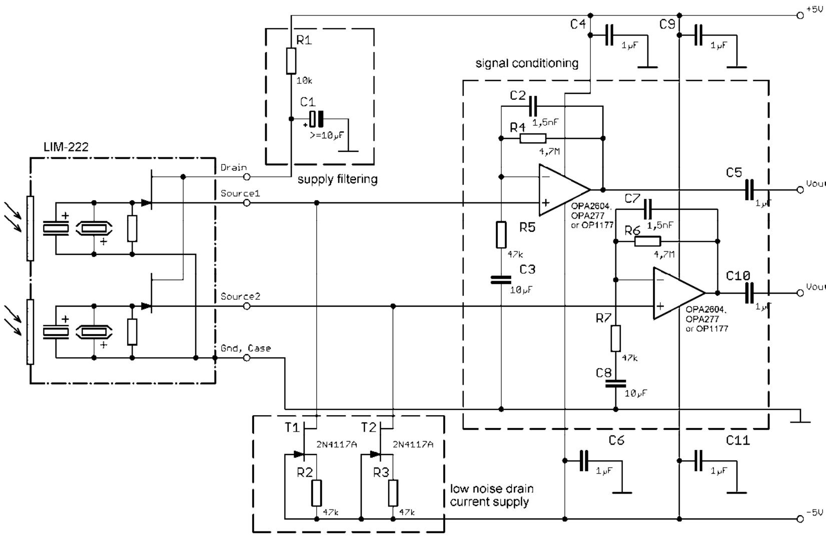


Fig 13: Using dual channel detectors. (±5 V or higher; (0.3 … 22) Hz; gain 101 dB)

Detector Basics

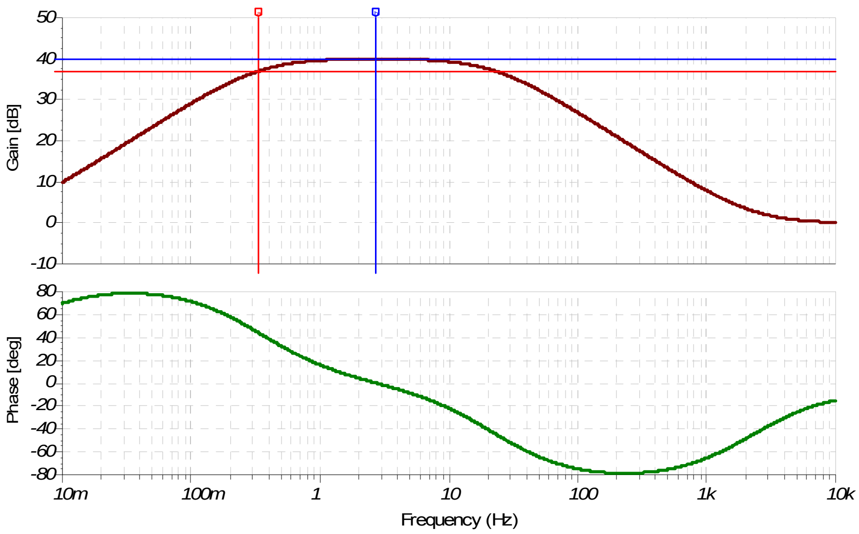


Fig 14: Gain and phase of preamplifier as per figure 13 vs. frequency

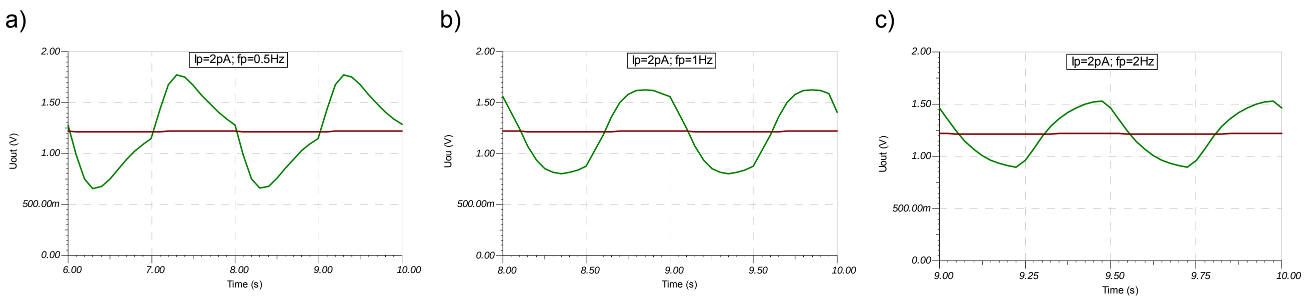


Fig 15: U_{out} of detector and preamplifier as per figure 13 at different frequencies
a) 0.5 Hz b) 1 Hz c) 2 Hz (simulated)

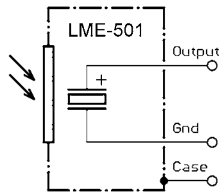
5 Current Mode

5.1 General information

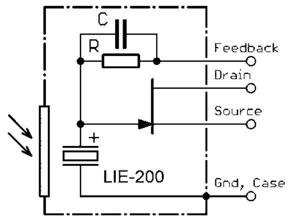
Current mode pyroelectric detectors are not as widely available as voltage mode ones. The most probable reason for this being that elementary pyroelectric detectors are mass-produced for light switches and motion detectors. Due to the complexity of the preamplifier circuit its use was limited to very 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

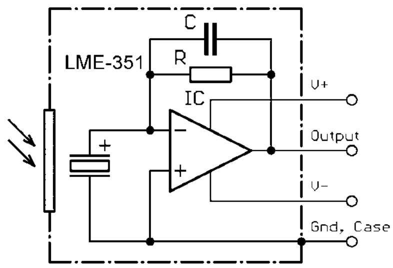
- Transistor style housing containing only the pyroelectric element.



- Transistor style housing containing the pyroelectric element, JFET and feedback resistor (an additional feedback capacitor of several picofarad (pF) is also possible). The integrated feedback capacitor prevents so-called gain peaking.



- Transistor style housing containing the pyroelectric element (also available with thermal compensation as LME-335) and a complete current voltage converter with low input bias current OpAmp.



- Transistor style housing containing the pyroelectric element (also available with thermal compensation as LME-336) and a complete current voltage converter with low input bias current OpAmp for single supply voltage (2.7 … 10) V.

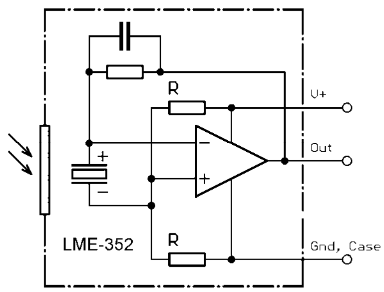


Fig 16: Four alternative pyroelectric detectors suitable for current mode

5.3 Wiring suggestions

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.

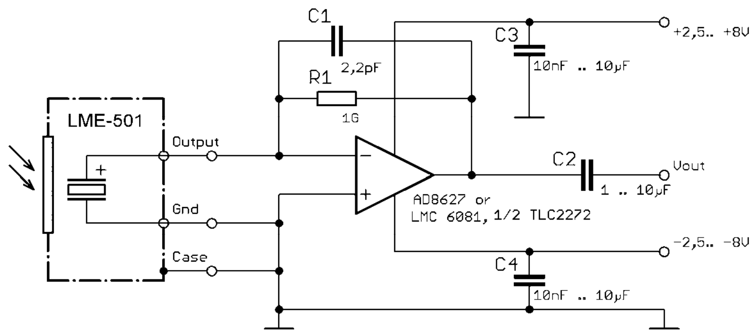


Fig 17: Circuit for current mode ((0.2 … 25) Hz; 1 V/nA) of the pyroelectric detectors and LME-501

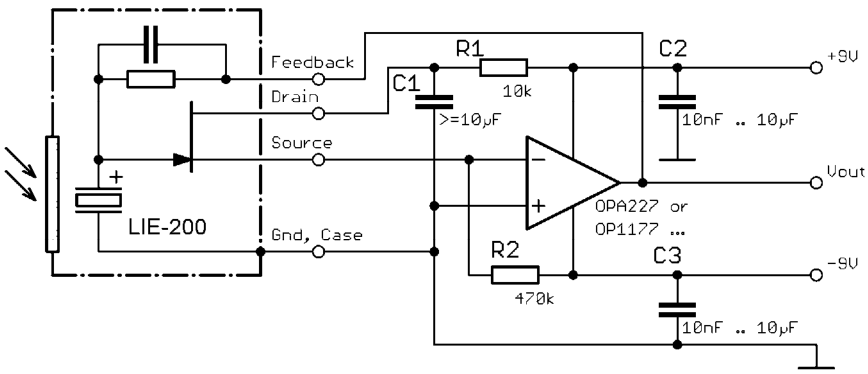


Fig 18: Circuit for current mode of the pyroelectric detector LIE-200

OpAmps with a low voltage noise should be used. Disadvantages of the circuitry depicted in figures 17 and 18 include:

- EMC (Electromagnetic Compatibility) problems due to parasitic capacities
- Permanent voltage offset across the pyroelectric element due to VGS (Gate-Source pinch-off voltage) of the JFET
- I_{GSS} (= gate reverse leakage current) 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.

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 a significantly higher responsivity can be achieved. The advantages of the integrated current mode detector are:

Detector Basics

- High responsivity (R_V approximately 90,000 V/W) and high stability
- Very low output offset (< ±5 mV)
- Low electrical time constant, short warm-up phase and fast recovery time
- No signal and detectivity loss when using the parallel compensation in thermal compensated detectors

Following are two examples for simple application circuits using a current mode detector. Since the thermal and electrical time constant from the LME-336 and LIM-262 are in the same range the behavior of their detector output signal for different frequencies is comparable (see figure 20).

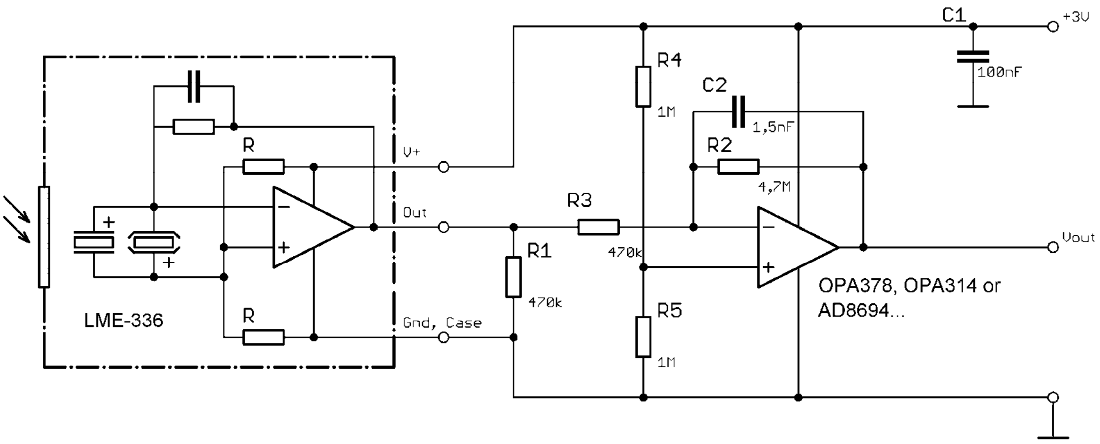


Fig 19: Circuit for current mode (typical R_v 90,000 V/W) of the pyroelectric detector LME-336 (2.7 ... 10) V

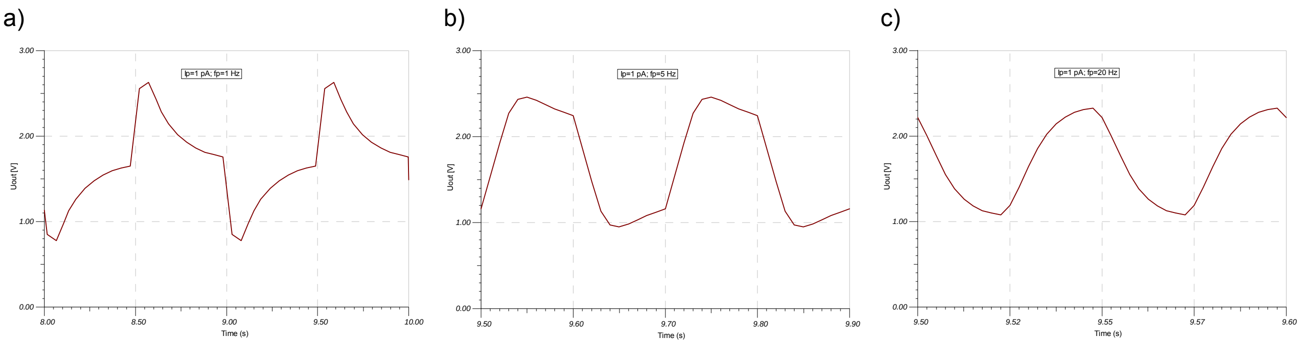


Fig 20: Signal voltage U_{out} of detector and preamplifier as per figure 19 at different frequencies

a) 1 Hz b) 5 Hz c) 20 Hz (simulated)

Detector Basics

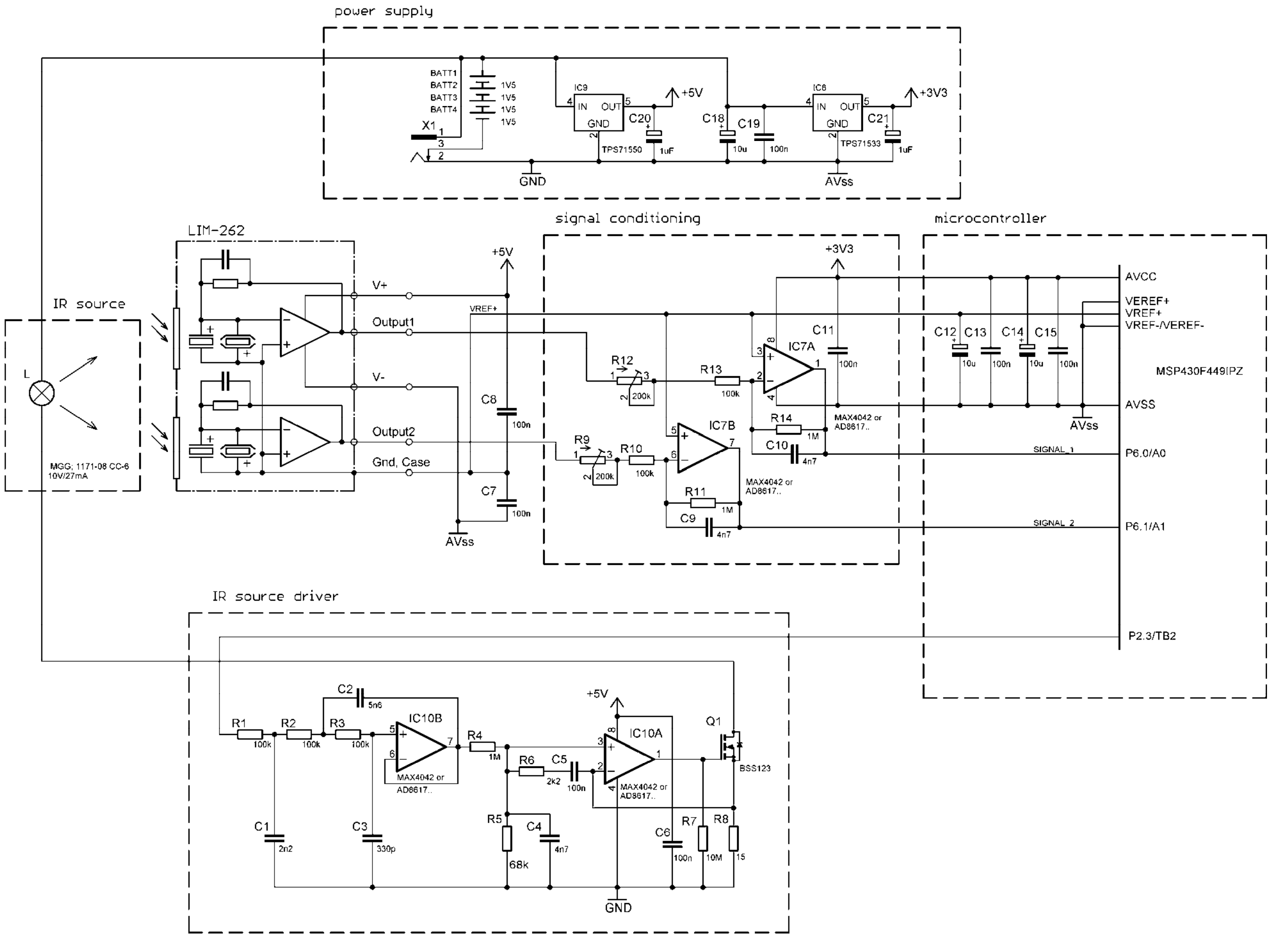


Fig 21: Circuit for current mode of the pyroelectric detectors LIM-262 (typical Rv 60,000 V/W)

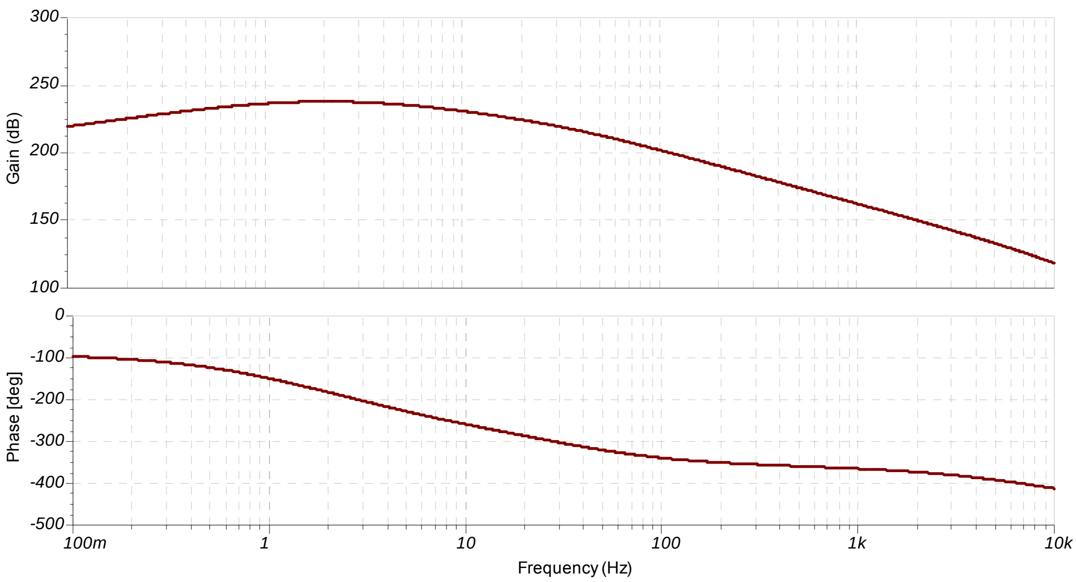


Fig 22: Gain and phase of preamplifier as per figure 21 vs. frequency

6 Infrared Sources

The application of a suitable IR source depends on the actual case of operation. Numerous sources with different emission characteristics are available. In the chapter 'Spectral Emission of IR Sources' some spectra are described. For simple applications incandescent lamps can be used. For more demanding uses e.g. hot plates are applied. The operation of LED's is limited due to their narrow spectral emission range and temperature dependency. The radiation of the light sources always needs to be chopped. Common frequencies are between 0.1 and 100 Hz. One possibility to realize this is the mechanical interruption of the radiation with a chopper wheel. An alternative is the electronic modulation/pulsing of the source (for example: lamp 6 V/115 mA T1 1160-08 (MGG); hot plate 6.5 V/135 mA MIRL17-900 (Intex) or IR-LED). For the realization different circuits can be used. An incandescent lamp typically is chopped with a few Hz (up to 10 Hz), the control circuit always needs to be adapted to the used lamp. The maximum chopper frequency for a hot plate source is in the range of up to 100 Hz. The electronic drive of the IR source MIRL17-900 with constant voltage driver is shown in figure 23.

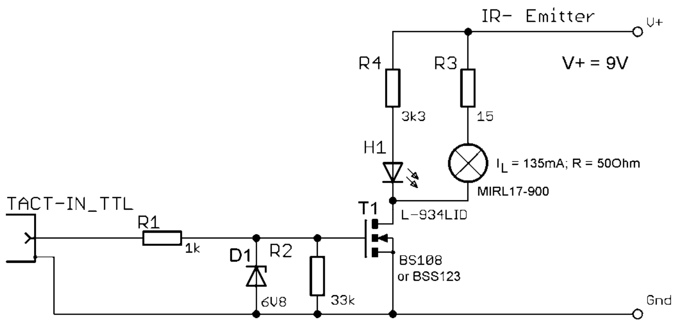


Fig 23: Example: Source MIRL17-900 (Intex) with constant voltage driver

An electronic drive independent of the supply voltage [+V = (8 ... 18) V DC] can be realized with a constant current source. Figure 24 gives an example for this circuit with additional adjustment of the lamp currents for lighting and dark lighting.

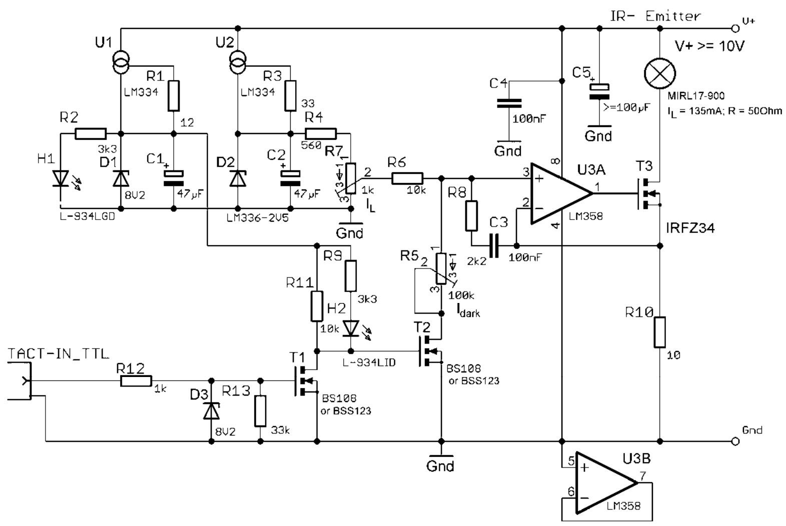


Fig 24: Example: Source MIRL17-900 (Intex) with constant current driver

7 Low Noise Power Supply

Batteries (Alkaline, Silver oxide-cell, Lithium cell) are a good choice for the detector supply as they have a very low ground noise. Generally linear dropout controllers can be used for the supply of both positive and negative voltage. Typical fixed controller IC's are to be seen in figure 25 and 26.

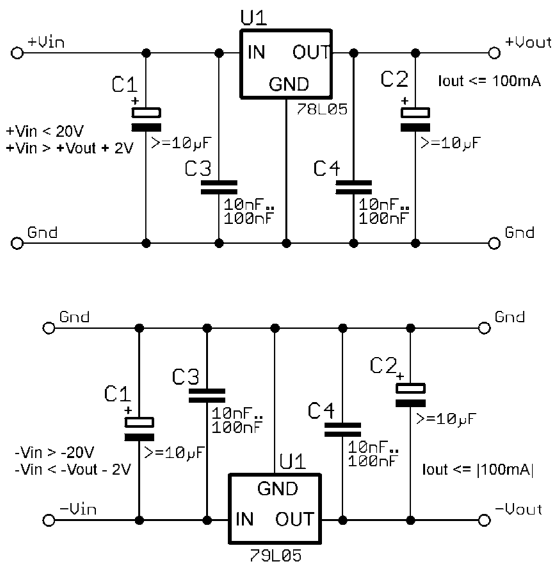


Fig 25: L78L05 fixed +5 V and L79L05 fixed -5 V

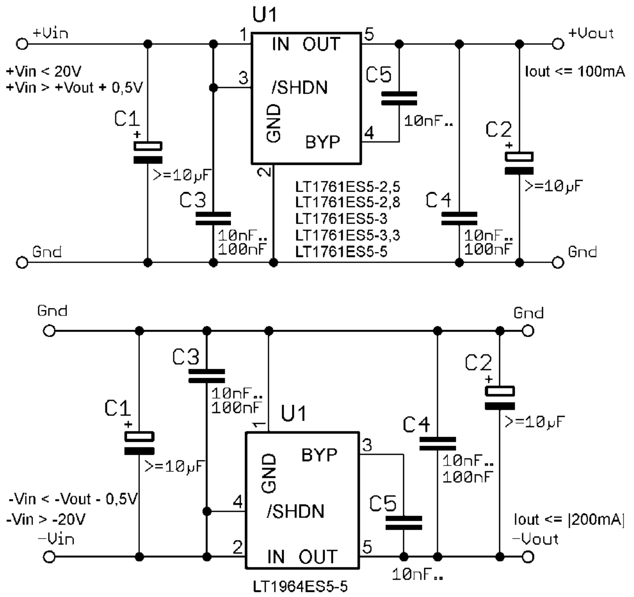


Fig 26: LT1761ES5-X (X=fixed voltage) and LT1964ES5-5 fixed (-5.0 V)

For variable supply voltages the controllers LM317LZ (positive voltage) / LM337L (negative voltage) are a good choice. To achieve an adjustable output with declined proprietary current consumption LT1761ES5-BYP (1.3 ... 20) V (see figure 27) and LT1964ES5-BYP (-1.3 … -20) V can be used. We recommend to employ ceramic capacitors respectively solid tantalum capacitors with a small equivalent series resistance (ESR) and a low temperature coefficient.

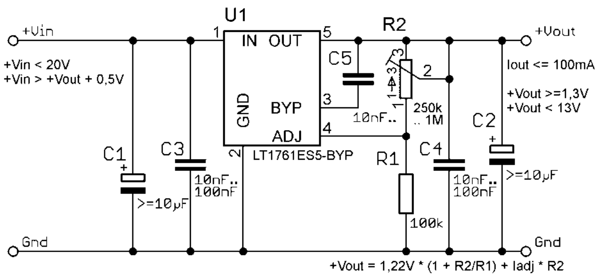


Fig 27: Variable power supply LT1761ES5-BYP for positive voltage

Power supply for InfraTec CMOS OpAmp detectors

For most InfraTec detectors a split power supply (±2.2 ... ±8) V is used. The new detectors with ultra low power consumption, e. g. LME-336 or LME-352, are equipped with a single supply OpAmp (2.7 … 10) V. For customized detectors InfraTec can also integrate different operational amplifiers.