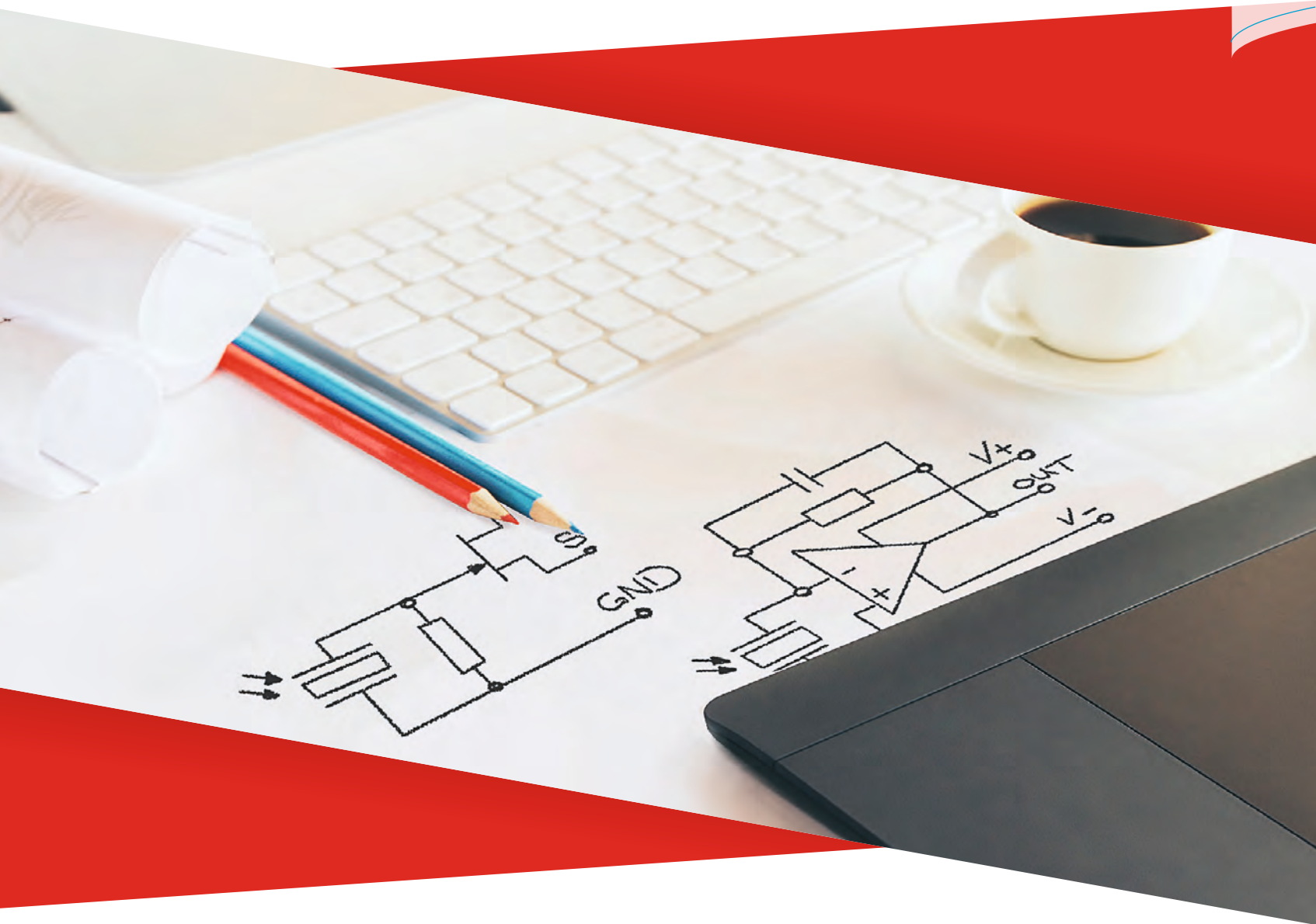


Integrated Amplification

Functionality and properties of detectors using current or voltage mode operation



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The charge generated by the pyroelectric effect can be measured as a current. Due to the high output impedance of the pyroelectric chip, it is necessary, however, to convert the current to a quantity which can be more easily evaluated. There are two possible operating modes:

- The **voltage mode** is one option and its basic circuit is shown on the left of Figure 5. The pyroelectric current is initially converted into a voltage by an RC network and afterwards it is converted to a lower impedance.
- The **current mode** is another option and is illustrated on the right of Figure 5. The pyroelectric current is permanently compensated by an OpAmp. The current required for this generates a voltage drop across an RC network in the feedback path which serves as measurement signal.

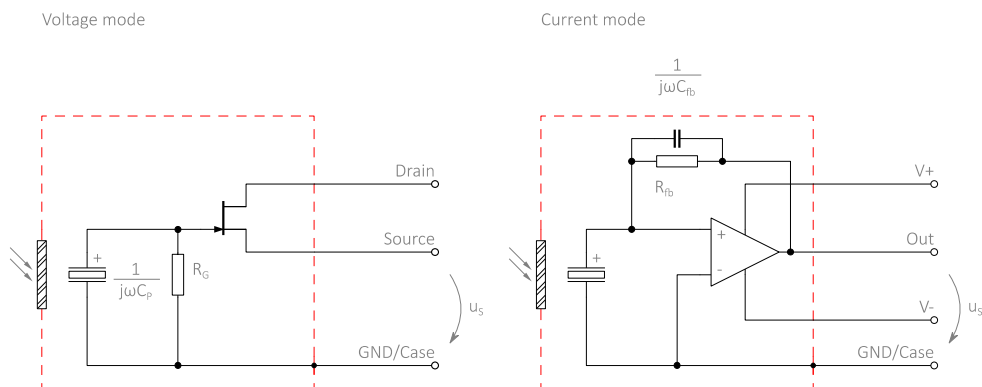


Figure 5: Basic preamplifier circuits in voltage mode and current mode

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2.1 Voltage Mode

2.1.1 Fundamentals

Thanks to its easy implementation, inexpensive components and small space requirement, the voltage mode has been the most widespread operating mode for pyroelectric detectors for decades.

A resistor is connected parallel to the pyroelectric element. The pyroelectric current $\dot{I}_p$ (10) flows through this RC network and causes a voltage drop. However, a direct measurement is not possible because the current magnitude is in the order of several picoamperes and the voltage is in the range of a few millivolts. For this reason, the voltage across the resistor is converted by a JFET in source follower circuit into a signal of lower impedance. Its evaluation is then much easier. The voltage gain A_V achievable in this way is a result of the forward transconductance of the JFET g_{fs} and the source resistance R_S :

$$A_V = \frac{g_{fs} R_S}{1 + g_{fs} R_S} \leq 1. \quad (21)$$

The voltage gain is always less than or equal to one and it is typically 0.8 for a source resistance of 47 k Ω . The resistance at the output is considerably lower than at the input. Thus, the main purpose of the JFET is not the voltage amplification but the impedance conversion.

Detectors in voltage mode as shown in Figure 6 have the following typical features:

- 1/f behaviour of responsivity and noise in the frequency range 1 ... 100 Hz. The result is a constant signal-to-noise ratio over this frequency range.
- To achieve a high performance of the detector, it is necessary to use resistance values of at least 10 G Ω .
- A higher resistance reduces the noise above the thermal corner frequency. It does not have an effect on the signal of the detector in this frequency range though.
- The resistors necessary for the impedance conversion are integrated into the welded metal housing of the detector by InfraTec to protect them effectively from environmental influences such as impurities and moisture.
- The output signal of detectors in voltage mode corresponds to the time integral of the incident infrared radiation. The integrating behaviour effectively suppresses high-frequency fluctuations of the radiation.
- The RC network of detectors in voltage mode consists of the capacitance of the pyroelectric chip and the gate resistor so that, in general, the output signal is phase-shifted by 90° for excitation.

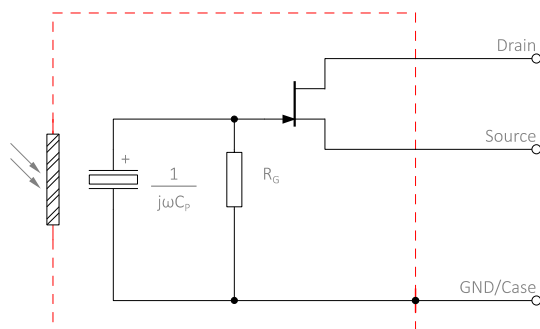


Figure 6: Inner circuitry of a typical detector in voltage mode such as LME-302

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2.1.2 Responsivity

As already discussed, the voltage drop generated by the pyroelectric current across the RC network is converted to a lower output impedance by the integrated JFET in voltage mode for a better evaluation. The RC network consists of the parallel connection of the gate resistor R_G and the electrical capacitance of the pyroelectric element C_P which can be calculated from the area of the pyroelectric element A_P , the thickness d_P and the permittivity $\epsilon_0 \epsilon_r$ of the pyroelectric material

$$C_P = \frac{\epsilon_0 \epsilon_r A_P}{d_P}. \quad (22)$$

If the pyroelectric current i_P flows through the RC network, then in the case of sinusoidal excitation the effective value of the output voltage $\tilde{u}_s$ can be specified as

$$\tilde{u}_s = R_G \tilde{i}_P \frac{1}{\sqrt{1 + \omega R_G C_P}}. \quad (23)$$

Using (12), (23), (8) and the definition of the electrical time constants

$$\tau_{el} = R_G \cdot C_P \quad (24)$$

the voltage responsivity of a detector in voltage mode can be specified as

$$R_V = \frac{\tilde{u}_s}{\tilde{\Phi}_P} = \frac{A_S T_F A_P p R_G}{G_P} \frac{\omega}{\sqrt{1 + (\omega \tau_{th})^2}} \frac{1}{\sqrt{1 + (\omega \tau_{el})^2}} \quad (25)$$

Since the electrical time constant is mostly larger than the thermal time constant in voltage mode and typical modulation frequencies are always above the thermal corner frequency, i.e. $(\omega \tau_{th})^2 \gg 1$ and $(\omega \tau_{el})^2 \gg 1$, (25) can be simplified as follows

$$R_V = \frac{A_S T_F A_P p}{G_P \tau_{th}} \cdot \frac{1}{\omega C_P} \quad (26)$$

When inserting (2) and (3) in (26) we finally obtain

$$R_V = \frac{A_S T_F}{A_P} \frac{p}{\epsilon_0 \epsilon_r c_P \rho_P} \frac{1}{\omega}. \quad (27)$$

Therefore, the responsivity in voltage mode is only determined by optical, geometrical and material parameters of the detector and decreases with increasing modulation frequency at $\frac{1}{f}$.

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2.1.3 Typical Signal Forms

The AC part of the signal generated by the modulated radiation is superimposed on the offset voltage of the JFET in voltage mode. The offset voltage is typically within the range of 400 ... 1,500 mV. Figure 7 shows the output signal of a detector LME-302 for typical excitation frequencies of 0.5 Hz, 3 Hz and 10 Hz. Depending on the impinging radiant power, typical signal amplitudes in voltage mode without narrow bandpass IR filters are within the range of 1 ... 100 mV.

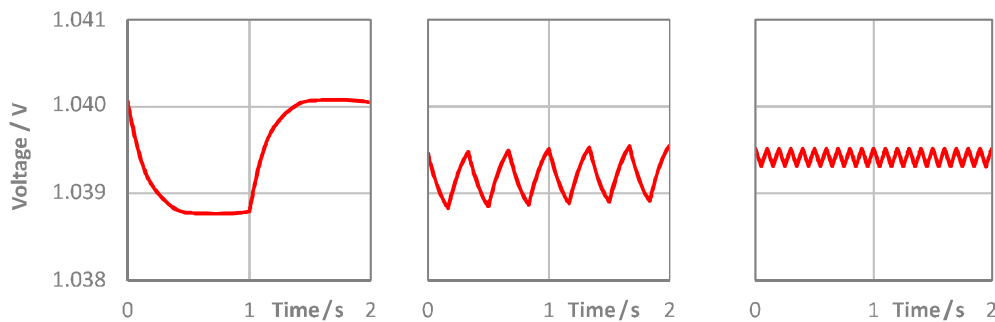


Figure 7: Typical time response of the output signal of a voltage mode detector LME-302 at 0.5 Hz, 3 Hz and 10 Hz (from left to right)

2.1.4 Noise

In voltage mode the transfer behaviour of the preamplifier is superimposed on the frequency response of the noise sources of the pyroelectric element. There are further noise sources which arise from the noise properties of the components and their interconnection. Thus, the JFET can be described by a noise voltage source and noise current source. The gate resistor constitutes a noise source as well. The effects of the individual noise sources on the detector output are illustrated in Table 2. The overall noise density N can be calculated by extracting the square root of the sum of squares of the noise densities of the individual noise sources:

$$N = \sqrt{N_T^2 + N_\delta^2 + N_{R_G}^2 + N_I^2 + N_V^2} \quad (28)$$

Noise source	Noise density	
Thermal noise of the gate resistor (Johnson noise)	$N_{R_G} = \sqrt{\frac{4k_B T}{R_G}} \frac{R_G}{\sqrt{1 + \omega\tau_{el}}} A_V$	(29)
Current noise of the JFET	$N_I = i_G \frac{R_G}{\sqrt{1 + \omega\tau_{el}}} A_V$	(30)
Voltage noise of the JFET	$N_V = e_N A_V$	(31)
$\tan(\delta)$ noise	$N_\delta = \sqrt{4k_B T \omega C_P \tan(\delta)} \frac{R_G}{\sqrt{1 + \omega\tau_{el}}} A_V$	(32)
Temperature noise of the pyroelectric chip	$N_T = \frac{R_V}{A_S} \sqrt{4k_B T^2 G_{th}}$	(33)

Table 2: Five essential noise sources and their effect on the output noise of a detector in voltage mode (e_N is the voltage noise density and i_G is the gate leakage current of the JFET.)

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Figure 8 shows the frequency response of the individual noise sources of a voltage mode detector as well as the resultant noise density of the detector output at room temperature. The thermal noise of the gate resistor is dominant for typical modulation frequencies in the range 1 ... 10 Hz. The gate leakage current of the JFET increases exponentially with temperature so that depending on the detector configuration the current noise density dominates the overall noise density starting from a temperature between 40 and 90 °C.

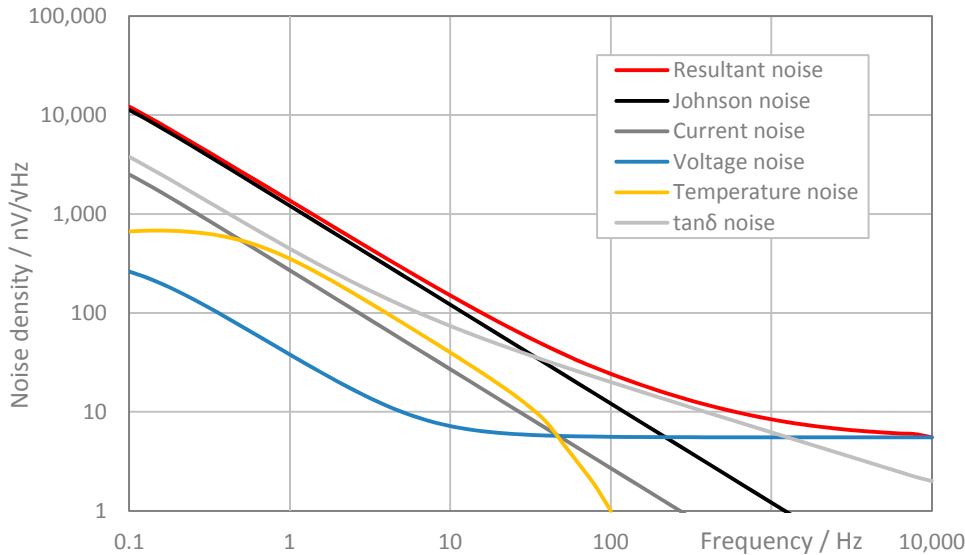


Figure 8: Frequency response of noise density and shares of the noise sources for a detector LME-302 in voltage mode

2.1.5 External Circuit

By choosing the largest possible source resistance, the value of the voltage gain (cf. equation (21)) approaches the value of one. Thus, the voltage gain is independent of interferences such as temperature dependencies and individual fluctuations of the forward transconductance g_{fs} of the JFET. This requirement conflicts with the desire for a low output impedance and low noise which is why the drain current I_D should not amount to more than one tenth of the saturation current I_{DSS} .

$$\frac{I_D}{I_{DSS}} \leq 0.1 \quad (34)$$

The JFET used by InfraTec has a typical saturation current of 1 mA. Using (34) drain currents are then in the range of 1 ... 100 μ A. An optimum value for InfraTec voltage mode detectors is 20 μ A.

Table 3 offers alternative options for setting the drain current in addition to the self-bias configuration using a source resistor R_S . The aim is to use a current source with as little temperature dependency as possible and with a high dynamic resistance.

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Circuit	Remarks
(a)	The simplest self biasing circuit - Strong dependence on drain current and amplification of the operating point - Asymmetrical output signal - Low dynamic range
(b)	Self biasing with negative supply and greater source resistance - Less dependence on temperature and amplification - Wider dynamic range compared to (a) - Symmetrical output signal possible
(c)	Current source with JFET - Low noise of the current source - High differential output resistance - Wider dynamic range compared to (a) - Symmetrical output signal possible
(d)	Current source with bipolar transistor and LED - High differential output resistance - Low temperature dependence - Wider dynamic range compared to (a) - Symmetrical output signal possible - Large number of additional components
(e)	Integrated current source - Stable temperature - Only one additional component - Cost-intensive solution - Depending on the component selected high inherent noise of the current source possible

Table 3: Options of low-noise current sources for the operating point adjustment of detectors in voltage mode

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2.1.6 Layout Recommendations

Detectors in voltage mode typically generate signal voltages of a few hundred microvolts. To protect these effectively against interferences it is recommended to do the following:

- Place the source circuit close to the detector.
- Keep the circuit tracks from the source of the detector to the subsequent amplifiers as short as possible and shield them by grounded tracks.
- Decouple the power supply of the detector from the analogue power supply by a low-pass filter and separate the analogue from the digital power supply.
- Design the ground connection radially and avoid ground loops. Please note that there is an internal connection between the detector housing and the ground pin for most of our detector types.

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2.2 Current Mode

The use of pyroelectric detectors in current mode has increased significantly in recent years thanks to the advantages of this operating mode as well as the availability of suitable integrable amplifiers. InfraTec already has many years of experience with current mode detectors and offers a wide range of detectors for applications in gas analysis or flame detection. Compared with voltage mode, current mode offers numerous advantages:

- The electrical time constant is considerably lower than in voltage mode. As a result both the thermal transient response and the response time of the detectors are markedly shorter.
- In contrast to voltage mode, adding thermal compensation does not reduce the responsivity. As a result drift effects of the operating point caused by temperature changes can be compensated with almost no performance losses.
- If the pyroelectric chip is only partially illuminated, then this does not lead to any reduction of the responsivity.
- Current-to-voltage conversion with voltage amplifications $\gg 1$ allows the output voltages of detectors in current mode to be considerably higher than in voltage mode. Consequently, current mode detectors can be operated directly with AD converters.

In contrast to voltage mode, current mode can be implemented at different integration levels Table 4 shows the different possibilities as well as their advantages and disadvantages.

2.2.1 Responsivity

In current mode the current generated by the pyroelectric effect is compensated by a transimpedance amplifier (TIA). Thus, the current flowing at the output of the OpAmp is the same as the short-circuit current of the pyroelectric element which causes a voltage drop across the feedback path. This voltage is present at the detector output and can be measured. To prevent any gain peaking of the OpAmp, an additional capacitance is necessary in the feedback path whose minimum value mainly depends on the characteristics of the OpAmp used in the detector. Thus, the electrical time constant is independent of the capacitance of the pyroelectric chip in current mode and can therefore be much shorter than in voltage mode. Typical values of electrical time constants in current mode are in the range of a few milliseconds, which is why the detector generates a significantly higher signal at higher modulation frequencies and has a shorter response time in the case of rapid changes of the incident radiant power.

The signal voltage of a current mode detector is calculated the same way as a voltage mode detector (cf. equation (23)).

$$\tilde{u}_s = R_{fb} \tilde{i}_p \frac{1}{\sqrt{1 + \omega \tau_{el}}} \quad (35)$$

The electrical time constant τ_{el} only results from the components of the feedback path

$$\tau_{el} = R_{fb} \cdot C_{fb} \quad (36)$$

and the responsivity is independent of the capacitance of the pyroelectric element.

$$R_V = \frac{\tilde{u}_s}{\Phi_p} = \frac{A_S T_F A_P p R_{fb}}{G_P} \frac{\omega}{\sqrt{1 + (\omega \tau_{th})^2}} \frac{1}{\sqrt{1 + (\omega \tau_{el})^2}} \quad (37)$$

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This equation can be further simplified for two limiting cases.

Case 1: The modulation frequency is between the thermal and electrical corner frequency.

$(\omega\tau_{th})^2 \gg 1$ and $(\omega\tau_{el})^2 \ll 1$, for typical detectors in the range of 3 ... 30 Hz

$$R_V = A_S T_F \frac{p}{c_p \rho_P d_P} R_{fb} \quad (38)$$

In this frequency range the responsivity is independent of the modulation frequency and proportional to the feedback resistance.

Case 2: The modulation frequency is higher than both corner frequencies.

$(\omega\tau_{th})^2 \gg 1$ and $(\omega\tau_{el})^2 \gg 1$, for typical detectors more than 100 Hz

$$R_V = A_S T_F \frac{p}{c_p \rho_P d_P} \cdot \frac{1}{\omega C_{fb}} \quad (39)$$

The responsivity then falls at $\frac{1}{f}$ and is inversely proportional to the capacitance of the feedback path.

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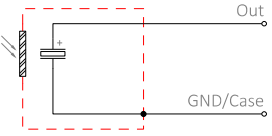
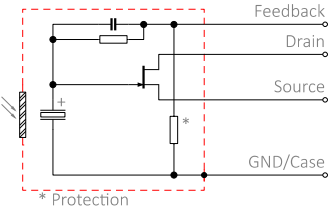
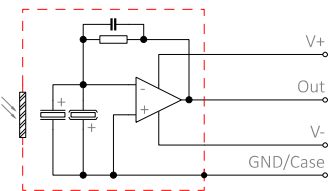
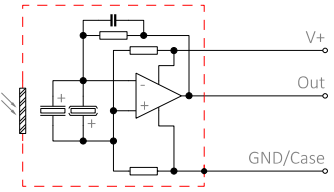
Description	Internal circuit	Remarks
Detector consists solely of an IR filter and pyroelectric element		■ Interference of high impedance signals is possible due to capacitive coupling ■ High value resistors are wired externally and are unprotected from environmental influences. Resistors with a value up to approx. 1 GΩ can be used only.
In addition to the IR filter and pyroelectric element, a JFET and feedback path consisting of a high value resistor and capacitor are integrated in the detector housing		■ The capacitor protects the external OpAmp from undesired oscillations ■ Permanent offset voltage due to the pinch-off voltage of the JFET ■ Gate leakage current of the JFET affects the temperature dependency of the current noise and the current noise of the detector
Detector with IR filter, pyroelectric element and integrated transimpedance amplifier		■ Very low static offset voltage max. ± 5 mV ■ OpAmp and feedback path are mounted in the detector housing and are therefore well-protected
Detector with IR filter, pyroelectric element, integrated transimpedance amplifier and reference voltage generation for operation on just one supply voltage		■ Offset voltage with a value half of the supply voltage e.g. at 3 V: $1500 \text{ mV} \pm 10 \%$ ■ OpAmp and feedback path are mounted in the detector housing and therefore are well-protected

Table 4: Internal circuit options of pyroelectric detectors in current mode

2.2.2 Typical Signal Forms

Depending on the internal circuit of the relevant detector (cf. Table 4), an offset voltage can be superimposed on the output signal in current mode. Due to the smaller electrical time constant, the rise time of the signal is shorter in current mode than in voltage mode. The signal amplitudes of detectors in current mode with comparable resistance values are also significantly higher. Depending on the feedback resistance and the impinging radiant power, signal voltages without narrow bandpass IR filters are in the range 100 mV ... 1 V. It has to be noted that the feedback resistance (5 ... 100 GΩ dependent on detector type) has a voltage dependency of the resistance value of around - 2 %/V. To minimize nonlinearities caused by the voltage level, the absolute value of the peak voltage should not exceed 1 V. Figure 9 shows the output signal of a detector LME-335 at selected excitation frequencies.

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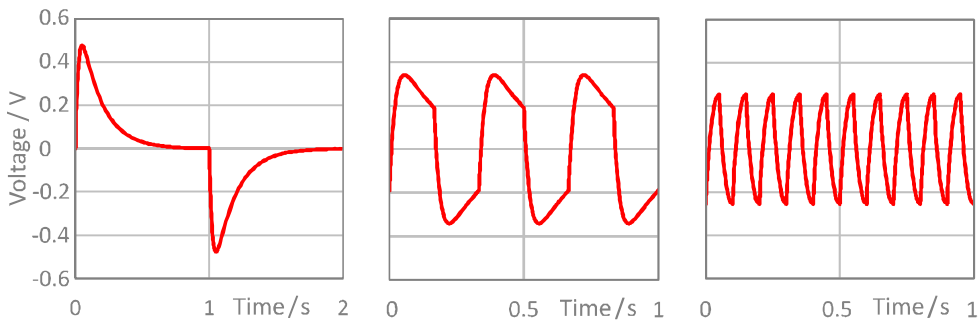


Figure 9: Typical signal forms of a current mode detector LME-335 at 0.5 Hz, 3 Hz and 10 Hz (from left to right)

2.2.3 Noise

To specify the noise density of a detector in current mode, the transfer function of the amplifier is superimposed on the noise sources of the pyroelectric element (cf. section 1.3). The noise sources of the OpAmp and the JFET can be illustrated similarly (section 2.1.4). The dominant noise source in different frequency ranges are the thermal noise of the feedback path, the noise due to the input leakage current as well as the voltage noise density of the OpAmp.

Figure 10 shows the resultant noise density for a detector LME-335 and the shares of the individual noise sources across the frequency range.

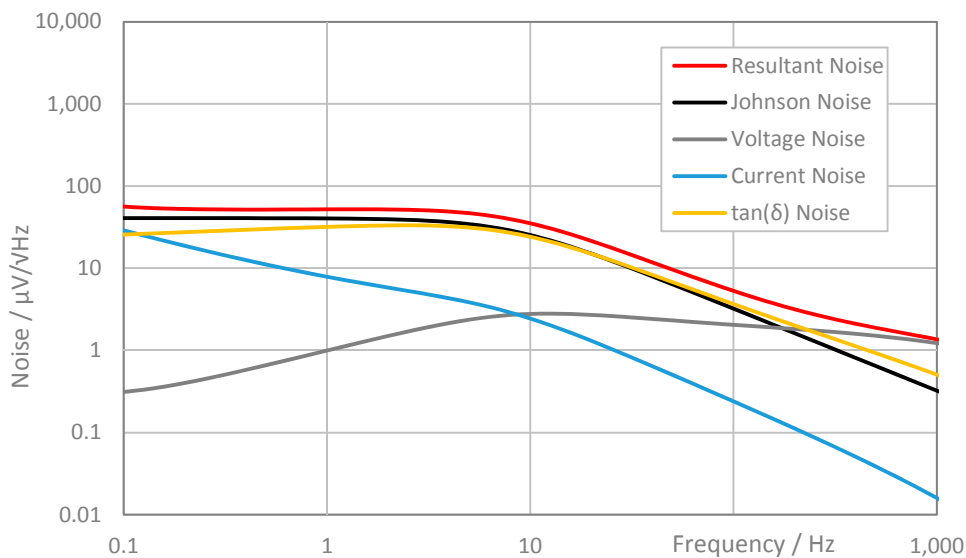


Figure 10: Frequency response of the resultant noise density and its shares for a detector LME-335 in current mode

Compared with detectors in voltage mode, the typical noise density in current mode is higher by a factor of 100 in the relevant frequency range of 10 ... 100 Hz.

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2.2.4 External Circuit

To ensure a high differential gain of the internal OpAmp, the load resistance should not be lower than 100 k Ω . Since inverting amplifiers only offer a small input impedance in most cases, the use of noninverting amplifiers is recommended for signal processing. We recommend to use a load resistor with a value between 100 k Ω and 1 M Ω for our current mode detectors.

2.2.5 Layout Recommendations

If detectors do not have an internal OpAmp (see Table 4), signals of high impedance are present at the detector output. Particular attention must be paid to the routing of the wiring and its shielding.

- The circuit tracks must be as short as possible and shielded from interfering sources.
- Solder joints, circuit tracks and external components must always be protected against contamination and moisture.

The output signal of detectors with an integrated OpAmp is significantly higher and has lower impedance which is why these detectors are much less sensitive to interference. These detectors can be used considering the universal design of the analogue circuit.

- Supply voltages and ground potentials must be decoupled from digital components.
- Grounded tracks of the individual analogue components should be designed radially and joined at one single point near the AD converter with the ground of the digital components.

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2.3 Summary and Comparison

Due to the progress in the design of integrated analogue silicon based circuits, InfraTec has – in addition to conventional detectors in voltage mode – been offering detectors with integrated OpAmp since 2003. By extending the product range of single and multi channel detectors in current and voltage mode, the ideal detector can be selected for each application.

The fundamental difference between both operating modes is the scale of the electrical time constants. In voltage mode the electrical time constant is calculated as a product of the gate resistor R_G and electrical capacitance of the pyroelectric chip C_p . The electrical time constant in voltage mode has typical values of approx. 2 s which is larger than the thermal time constant.

In current mode the pyroelectric current is converted into a measurable voltage by a current-to-voltage amplifier. Its amplification is frequency-dependent due to the low-pass behaviour of the feedback path and has typical values of 10 ... 200 V/pA. The electrical time constant of the detector is calculated from the components of the feedback path and can therefore be selected regardless of the capacitance of the pyroelectric chip. Typical values of the electrical time constants in current mode are in the range of 20 ms and are therefore smaller than the thermal time constant.

The thermal time constant itself is a measure for the thermal capacitance of the pyroelectric chip and its thermal coupling to its environment. It is independent of the operating mode and has typical values of 150 ms.

Figure 11 illustrates the different responsivity characteristics of current and voltage mode detectors across the modulation frequency. The different characteristics result from the fact that in voltage mode the thermal time constant is smaller than the electrical time constant whereas the reverse is true for current mode.

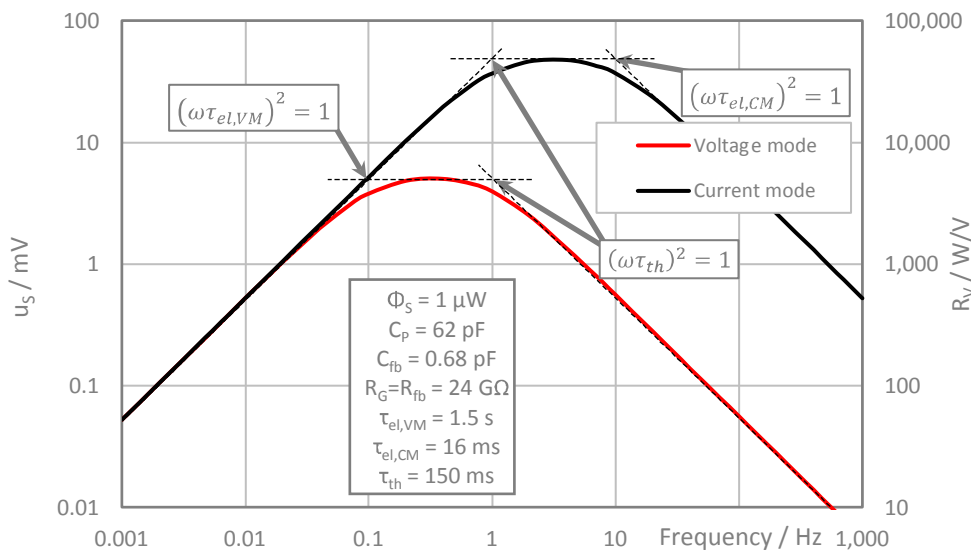


Figure 11: Comparison of the responsivity and signal of voltage and current mode detectors across the frequency

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Voltage mode detectors are typically operated with frequencies that are higher than the corner frequencies which are a result of both the electrical and the thermal time constants. The signal then decreases inversely proportional to the modulation frequency. Low frequency disturbances contribute significantly to the output signal. For example, when caused by fluctuations of the ambient temperature, they can be within the range of a few millihertz. Due to the large electrical time constant, the settling time of a voltage mode detector after a sudden excitation is typically about 20 s.

In current mode the detector is mostly operated between both corner frequencies. Between these frequencies the signal is at its maximum and only depends slightly on the frequency. The influence of low frequency disturbances on the output signal, for example by temperature changes, is about ten times less than in voltage mode. Due to its very short electrical time constant, the settling time of a detector in current mode is almost always determined exclusively by the thermal time constant and has typical values of approximately one second.

To adapt a detector in terms of signal, noise and sensitivity to environmental influences to a specific application, the value of the resistor (gate resistor in voltage mode or feedback resistor in current mode) can be varied while the remaining detector design remains unchanged. The following comments discuss the effects of such a variation.

In voltage mode the electrical time constant will still remain larger than the thermal time constant in most cases even if the resistance value is changed. The output signal for frequencies above the thermal corner frequency also remains unaffected by the change of the resistance value as Figure 12 (left) shows. The noise density is dominated by the Johnson noise of the resistance in the frequency range of 1 ... 10 Hz. The Johnson noise is indirectly proportional to the square root of the resistance value according to (29) and therefore a lower noise density can be achieved by selecting a larger resistance value.

Hence, when increasing the resistance value, the signal remains the same and the noise decreases. Consequently, the detectivity of a detector increases with increasing resistance in voltage mode as can be seen in Figure 12 (right).

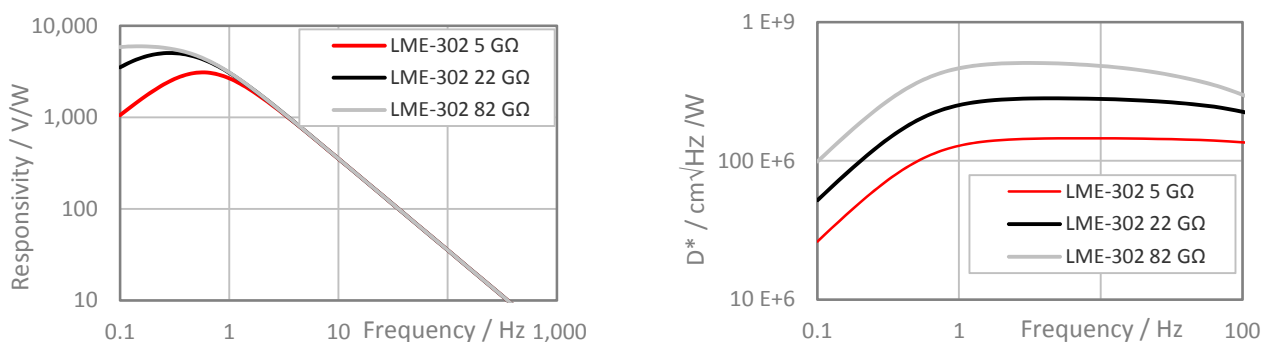


Figure 12: Frequency response of the responsivity (left) and detectivity (right) of detectors in voltage mode with different gate resistors

A decrease of the resistance value in turn leads to a smaller electrical time constant and faster settling time of the detector. The offset voltage is less dependent on the temperature as well. For this reason thermal compensation is usually not necessary for resistance values below 10 GΩ.

Unlike in voltage mode, an increase of the feedback resistance in current mode causes an increase of the responsivity as the comparison in Figure 13 (left) shows. Since the electrical time constant also shifts in the direction of the thermal time constant, the frequency range where the responsivity is constant decreases with increasing resistance.

The noise of the detector is affected significantly by the value of the feedback resistance as well. The noise density increases with the square root of the resistance.

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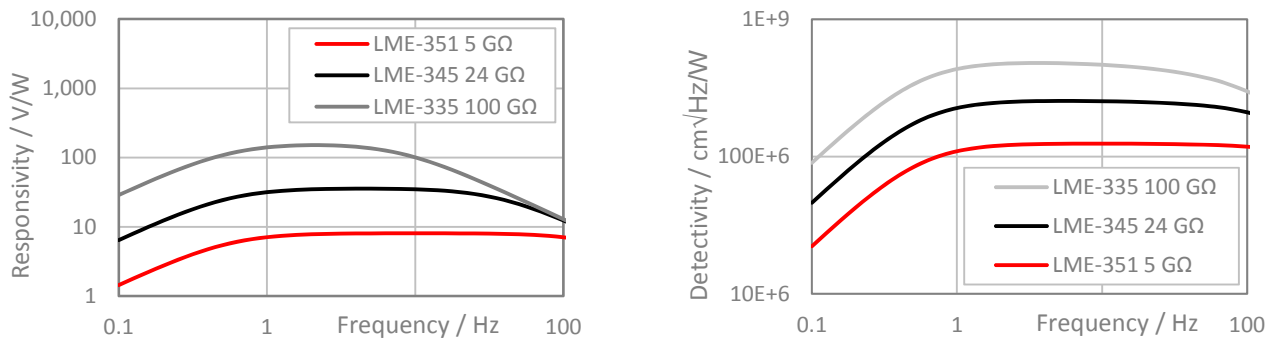


Figure 13: Frequency response of the responsivity (left) and detectivity (right) of detectors in current mode with different feedback resistances

Since the responsivity increases faster than the noise density, the detectivity also increases with an increasing resistance value as Figure 13 (right) illustrates. The $1/f$ behaviour of the responsivity is balanced by the $1/f$ behaviour of the noise density as far as possible and in a similar way as in voltage mode.

If the pyroelectric element is irradiated partially in current mode, the frequency behaviour of the signal and noise remains unchanged. The same applies if an additional pyroelectric element for thermal compensation is connected in parallel to the active element (compare section 3 as well).

In voltage mode, however, the detectivity decreases if thermal compensation is added. In the case of parallel compensation, this results from a decrease of the output signal and in the case of serial compensation from an increase of the noise density.

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Please see Table 5 for a comparison of the characteristics and typical parameters of current and voltage mode detectors.

	Voltage mode	Current mode
Thermal time constant	150 ms	150 ms
Electrical time constant	2 s	20 ms
Responsivity at 10 Hz	100 ... 1,000 V/W	5,000 ... 85,000 V/W
Noise density at 10 Hz	100 ... 500 nV/√Hz	10,000 ... 60,000 nV/√Hz
Settling time	20 s	1 s
Reduction of D* resulting from thermal compensation	30 %	< 10 %
Change of the signal due to changed resistance	None	$\propto R_{fb}$
Change of the noise due to changed resistance	$\propto \frac{1}{\sqrt{R_G}}$	$\propto \sqrt{R_{fb}}$
Influence of low frequency disturbances	High	Low

Table 5: Comparison of typical parameters of voltage and current mode detectors

Due to the large variety of current and voltage mode detectors with differing performance, InfraTec allows for the selection of a detector most suitable for your applications.