Basics

Conversion principle and parameters of pyroelectric detectors

Basic Principles of Pyroelectric Detectors

The pyroelectric effect was already known in ancient times (Theophrastos of Eresos 4th century B.C.). It first received its name commonly used today in 1824, however, by David Brewster (1781 – 1868), a Scottish physicist whom the Brewster-angle among other things is named after.

The widespread application in sensor technology began in the early 1970's. Today pyroelectric detectors are among the most commonly used thermal infrared detectors due to their simplicity, robustness and performance.

The core of a pyroelectric detector is the pyroelectric chip. The chip consists of a crystalline material with special properties. Crystals are formed from oppositely charged components, e.g. ions which are arranged in a regular structure, namely the crystal lattice. With 10 out of 32 crystal classes, the negative and positive centres of charge do not coincide in the crystal lattice. This results in a spontaneous electric polarisation and a polar axis. Such crystal classes are referred to as pyroelectric since the spontaneous polarisation is temperature-dependent. Sensor technology utilises this so-called pyroelectric effect. For this purpose a thin pyroelectric crystal (pyroelectric material) is coated with electrodes vertically aligned to the polar axis. The upper electrode of the crystal is coated with an absorbent layer (black layer). If infrared radiation strikes this layer, the pyroelectric material heats up and surface charges occur. If the radiation is switched off, charges of reverse polarity occur. The charges are very small though. Before they can equalise due to the finite internal resistance of the crystal, extremely low-noise and low-leakage-current field-effect transistors (JFET) or operational amplifiers (OpAmp) convert the charges into a signal voltage.

To explain the function of a pyroelectric detector systematically, the individual conversion processes are analysed in more detail:

- The optical-thermal conversion, i.e. the generation of temperature changes resulting from changes of the incident infrared radiation.
- The thermal-electrical conversion, i.e. the generation of charges resulting from temperature changes.
- The conversion of the charges into currents and voltages and their electrical amplification, the result of which is the output signal of the detector.

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1.1 Optical-thermal Conversion

The radiation flux Φ striking the detector window first passes through the optical filter with the transmission T_F and subsequently impinges on the pyroelectric chip. This results in a temperature increase of the pyroelectric chip $\Delta\vartheta_P$ which is proportional to the optical absorption A_P and inversely proportional to its heat capacity H_P. At the same time the applied heat is discharged again via the environment – the chip holder in particular – with the temperature ϑ_0, which can be characterised by a thermal conductance G_P. These two competing processes – heating of a thermal mass and cooling due to heat conduction – can be described by the term thermal conductivity which is entered as a parameter in the heat conduction equation. This is a partial differential equation that generally has to be solved taking the boundary conditions and initial conditions into account.
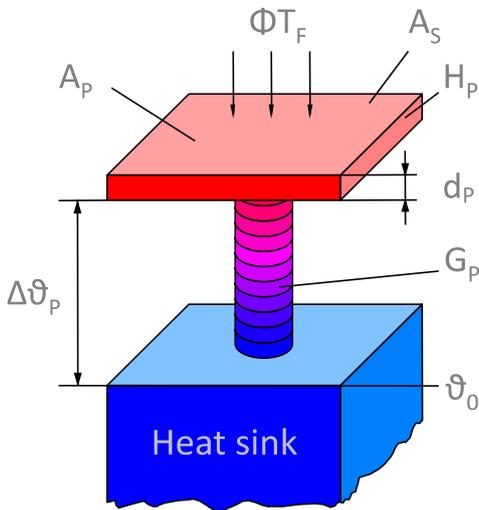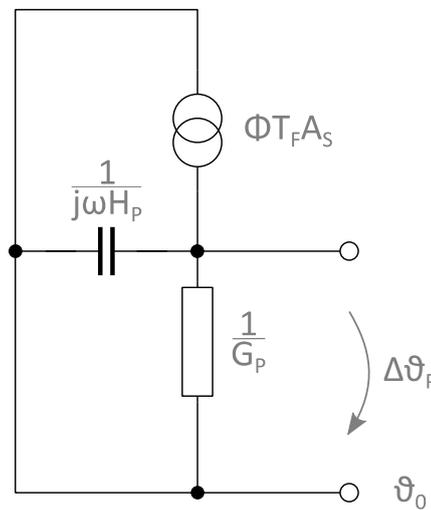

Figure 1: Thermal model

Figure 2: Equivalent circuit

Let us take a different approach here. For practical purposes it is quite sufficient to focus on the steady state. Since each periodic signal can be represented as the sum of sinusoidal signals over time, we will restrict ourselves to such as well. By using equivalent circuits corresponding to electrical resonant circuits, it is possible to specify simple solutions where time constants are used as parameters. Consequently, the temperature increase of the pyroelectric chip results from

$$\Delta\tilde{\vartheta}_P = \frac{A_S\, T_F\, \tilde{\Phi}}{G_P\, \sqrt{1 + \omega^2\, \tau_{\text{th}}^2}} \tag{1}$$

with the thermal time constant

$$\tau_{\text{th}} = \frac{H_P}{G_P}. \tag{2}$$

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The heat capacity H_P is derived from the two material constants specific heat capacity c_P and density ρ_P of the pyroelectric material as well as from the volume of the pyroelectric chip which in turn is the product of its surface area A_P and thickness d_P.

$$H_P = c_P \, \rho_P \, A_P \, d_P \tag{3}$$

To achieve a sufficiently large signal and as a result a good signal-to-noise ratio, the temperature change should be as big as possible. Relating to the detector this means that the absorption in the pyroelectric chip and the transmission in the passband of the optical bandpass filter must be high. In terms of the thermal conductance, a compromise is necessary because its reduction causes both a larger temperature difference and a larger thermal time constant. To ensure an optimal value of ≈ 150 ms for the thermal time constant, the heat capacity of the pyroelectric chip must not be too low which is achieved by optimising its thickness d_P.

To discuss this result, we will consider two limiting cases: very low and very high frequencies of the radiant flux.

For frequencies in the range of several millihertz $\omega^2 \tau_{th}^2 \ll 1$)

$$\Delta \tilde{\vartheta}_P = \frac{A_S \, T_F \, \tilde{\Phi}}{G_P} \tag{4}$$

the temperature difference is independent of the frequency and constant. The temporal change of the radiation occurs so slowly that the thermal processes can follow without any problem.

For frequencies higher than 10 Hz ($\omega^2 \tau_{th}^2 \gg 1$)

$$\Delta \tilde{\vartheta}_P = \frac{A_S \, T_F \, \tilde{\Phi}}{G_P \tau_{th}} \cdot \frac{1}{\omega} \tag{5}$$

the temperature difference decreases with an increasing frequency. The thermal processes can follow the temporal change of the radiation increasingly less.

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1.2   Thermal-electrical Conversion

The temperature change $\Delta\,\vartheta_P$ of a pyroelectric element generates surface charges on its electrodes. The magnitude of the surface charges Q is proportional to the surface area A_P and the strength of the pyroelectric effect which is characterised by the pyroelectric coefficient p. The effect occurs similarly with heating as well as cooling. The resulting charges only differ with respect to the sign.

$$Q = p\,A_P\,\Delta\vartheta_P \tag{6}$$

The charges discharge in a closed circuit and yet a change in charge over time is simply a current.

$$i_P = p\,A_P\,\frac{d\Delta\vartheta_P}{dt} \tag{7}$$

In the steady state and with sinusoidal excitation we obtain using (1):

$$\tilde{\imath}_P = \omega\,p\,A_P\,\frac{A_S\,T_F\,\widetilde{\Phi}}{G_P\,\sqrt{1 + \omega^2\,\tau_{th}^2}} \tag{8}$$
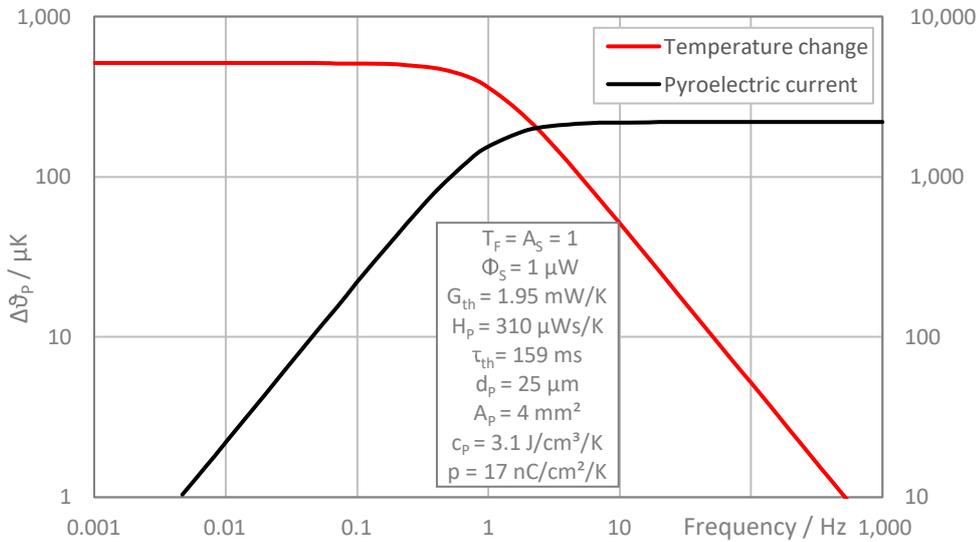

Figure 3: Frequency dependence of the temperature change and short-circuit current of a pyroelectric element

To discuss this result, we will consider the two limiting cases again: very low and very high frequencies of the radiation flux.

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For frequencies in the range of several millihertz ($\omega^2 \tau_{th}^2 \ll 1$)

$$\tilde{\imath}_P = \omega \, p \, A_P \, \frac{A_S \, T_F \, \widetilde{\Phi}}{G_P} \tag{9}$$

the pyroelectric current increases linearly with the frequency. Very slow temperature changes, e.g. through the change of the ambient temperature, therefore only make minor contributions to the signal.

For frequencies higher than 10 Hz ($\omega^2 \tau_{th}^2 \gg 1$)

$$\tilde{\imath}_P = p \, A_P \, \frac{A_S \, T_F \, \widetilde{\Phi}}{G_P \, \tau_{th}} \tag{10}$$

the pyroelectric current is independent of the frequency, constant and maximum. This is the preferred operating range of a pyroelectric detector.

Figure 3 shows the frequency dependence of the temperature change and the short-circuit current of a typical pyroelectric element. The temperature change shows a low-pass characteristic. The thermal corner frequency f_{th} is derived from the thermal time constant:

$$f_{th} = \frac{1}{2 \, \pi \, \tau_{th}} \tag{11}$$

It is 1 Hz for the example shown in Figure 3. While the temperature change reaches a saturation value of 513 µK below the corner frequency, the pyroelectric current increases to a saturation value of 2.2 pA above the corner frequency.

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1.3 Important Characteristic Values

Pyroelectric detectors are characterised by their responsivity, by the noise they produce as well as by the ratio of these two parameters. To compare different detectors, the specific detectivity has proved successful. All parameters, responsivity, noise and specific detectivity, are specified by InfraTec for each detector type on the data sheet.

1.3.1 Responsivity

The responsivity R is generally defined as the ratio of the output signal to the input signal. With pyroelectric detectors, the input signal normally is the effective value of the sinusoidal modulated radiant power $\tilde{\Phi}$ that impinges on the radiation-sensitive chip. The output signal is the effective value of the fundamental wave of the signal voltage $\tilde{u}_S$.

$$R_V = \frac{\tilde{u}_S}{\tilde{\Phi}} \tag{12}$$

Since both the pyroelectric conversion and the amplifier elements depend on the excitation frequency, the responsivity is frequency dependent as well. Figure 4 illustrates the dependence using the LME-336 as an example.
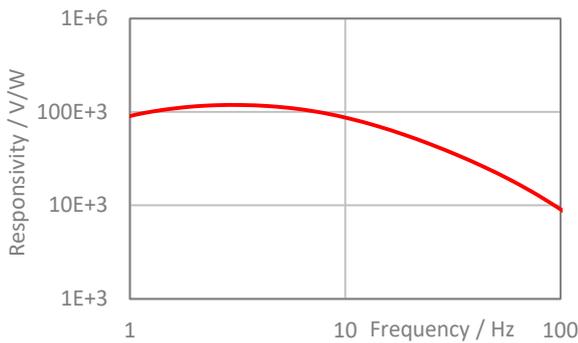

Figure 4: Typical frequency response of the responsivity of a current mode detector. The single channel detector LME-336 in single supply operation is used as an example.

1.3.2 Noise

Noise is defined as a broadband, random signal which modifies the measurement signal and does not contain additional information. To characterise noise, we use the temporal mean square value of the noise voltage $u_N(t)$ which is described as noise density N with respect to the measurement bandwidth Δf.

$$N = \frac{\sqrt{\overline{u_N(t)^2}}}{\Delta f} \tag{13}$$

If the noise density does not depend on the frequency, then by analogy to visible light we speak of white noise. However, this does not apply to pyroelectric detectors. Typical frequency responses of the noise density are therefore specified for each detector type on the data sheet.

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Since the amplitude cannot be predicted due to the randomness of the noise, we calculate the effective value $\tilde{u}_N$ of the noise voltage using (14). In the case of a Gaussian distribution in the frequency range, the effective value $\tilde{u}_N$ of the noise voltage is equal to the standard deviation of the random signal. f_l and f_h are the lower and upper limit of the range with significant noise components.

$$\tilde{u}_N = \sqrt{\int_{f_l}^{f_h} N^2 df} \tag{14}$$

Amplitude as a function of the effective value of the noise	Probability by which the noise voltage is lower than the amplitude value
$\tilde{u}_N$	68.3 %
$2 \cdot \tilde{u}_N$	95.4 %
$3 \cdot \tilde{u}_N$	99.7 %
$3.3 \cdot \tilde{u}_N$	99.9 %

Table 1: Correlation between the amplitude of the noise and the probability of falling below the amplitude value

Since all noise sources of a pyroelectric detector are statistically independent, they can be analysed individually. Their combined impact on the detector output can be determined by extracting the square root of the sum of squares of all noise voltages.

If we solely look at the pyroelectric chip in its thermal environment, then the heat exchange of the chip with the environment as well as the dielectric losses within the material will contribute to the noise.

Noise source	Noise density	
Thermal noise	$N_T = \sqrt{4k_B T^2 G_{th}}$	(15)
$\tan(\delta)$ noise of the pyroelectric element	$N_\delta = \sqrt{4k_B T \omega C_P \tan(\delta)}$	(16)

These terms can be derived by statistical physics. T is the (absolute) temperature, k_B the Boltzmann constant and $\tan(\delta)$ the loss factor of the capacity of the pyroelectric element. The chapters about "Noise" will discuss the noise components of the preamplifier as well as the impact of the noise sources on the output of a voltage mode detector or a current mode detector in detail later on.

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1.3.3 Specific Detectivity

Specific detectivity D* is a benchmark for different detectors. It corresponds with the signal-to-noise ratio normalised to noise bandwidth Δf, area of the pyroelectric element A_P and radiant power Φ.

$$D^* = \frac{\sqrt{A_P}\, R_V}{N} = \frac{\sqrt{A_P \Delta f}}{\widetilde{\Phi}} \cdot \frac{\tilde{u}_S}{\tilde{u}_N} \tag{17}$$

The analysis of the noise and the definition of the detectivity lead to the result that a maximum value of

$$D^*_{max} = \frac{1}{\sqrt{16\, k_B T^5 \sigma}} \tag{18}$$

is possible if we assume that the temperature noise represents the only unavoidable noise source. σ is the Stefan-Boltzmann constant. At a temperature of 25 °C this theoretical limit is

$$D^*_{max,25°C} = 1.8 \cdot 10^{10}\, \frac{cm\sqrt{Hz}}{W}.$$

1.3.4 Noise Equivalent Power

The noise equivalent power NEP is often used to compare different detectors, too. It describes the radiant power that must impinge on the detector to achieve a signal-to-noise ratio of 1.

$$NEP = \frac{N}{R_V} \tag{19}$$

The relation of the noise equivalent radiant power to the specific detectivity can be shown by inserting (17) in (19):

$$NEP = \frac{\sqrt{A_P}}{D^*} \tag{20}$$

Chesterfield

Headquarters
Dresden

Shanghai

Dallas

Headquarters

InfraTec GmbH
Infrarotsensorik und Messtechnik
Gostritzer Str. 61 – 63
01217 Dresden / GERMANY
Phone   +49 351 871-8625
Fax   +49 351 871-8727
E-mail   sensor@InfraTec.de
Internet www.InfraTec.de

China office

InfraTec Representative
Greater China
c/o German Industry & Commerce
Greater China
Shanghai / PEOPLE'S REPUBLIC OF CHINA
Phone   +8621 68758536 ext 1633
E-mail   sensors@InfraTec.cn
Internet www.InfraTec.cn

UK office

InfraTec infrared Ltd.
Chesterfield / UK
Phone   +44 1246 267562
Fax   +44 1246 269381
E-mail   sensor@InfraTec.co.uk
Internet www.InfraTec.co.uk

USA office

InfraTec infrared LLC
Plano, TX / USA
Phone   +1 877 797 6748
Fax   +1 877 389 2668
E-mail   sensor@InfraTec-infrared.com
Internet www.InfraTec-infrared.com

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