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Comparison of Pyroelectric and Thermopile Detectors

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Abstract:
Thermal infrared detectors are distinguished by the advantages of a wide wavelength response, no requirement for cooling, high-temperature stability, high signal-to-noise ratio and low cost. Consequently, they are widely used in consumer products and in instrumentation. In the literature one can find many publications with regard to details either of pyroelectric detectors or thermopiles but a comparison of both thermal detectors could seldom be found. The main principles and the basic design of both the pyroelectric detector and the thermopile will be discussed as a starting point. Then the electro-optical properties of typical representatives of both the pyroelectric detector and the thermopile produced from our companies will be compared. Measurement results of blackbody responsivity, noise, and specific detectivity and spectral response will be displayed and discussed. The authors will conclude with a discussion of the advantages and disadvantages of pyroelectric detectors and thermopiles, including the electro-optical properties as well as the costs and typical applications of both thermal detector types.

Key words: Pyroelectric Detector, Thermopile Detector, Responsivity, Specific Detectivity.

Introduction

Thermal infrared detectors are distinguished by the advantages of a wide wavelength response, no requirement for cooling, high-temperature stability, high signal-to-noise ratio and low cost. Consequently, they are widely used in medical, industrial, military and consumer products [1]. Publications exist with information about pyroelectric or thermopile detectors, but direct comparisons of the two detectors is rarely found. Therefore we decided to compare pyroelectric detectors and thermopiles and chose two typical representatives from the production portfolio of our companies.

Principles and Basic Design of Pyroelectric and Thermopile Detectors

Both the pyroelectric and the thermopile detectors are thermal detectors. The thermal conversion is the basis for a high responsivity and signal-to-noise ratio and should result in a high temperature change ΔT_S of the respective radiation sensitive element. Figure 1 represents a simplified thermal model [2]. The radiation sensitive element is characterized by the absorption rate α, the thickness t_P, the area A_S, 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.

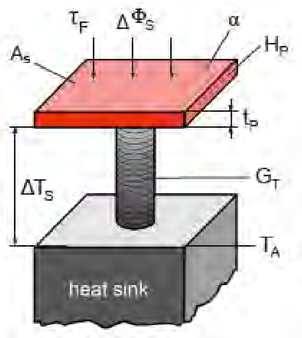

Fig. 1. Simplified thermal model of pyroelectric and thermopile detectors

Using the thermal time constant

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

the temperature difference results in

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

or for sinusoidal agitation in the steady state

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

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For significant temperature differences to occur the absorbance α has to be as near to 100% as possible. This can especially be achieved by the use of a special absorption layer. The heat capacity value H_P has to be 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.

The thermal to electrical conversion is different in pyroelectric and thermopile detectors. In pyroelectric detectors the thermal to electrical conversion is due to the pyroelectric effect p. A very thin pyroelectric plate with top and bottom electrodes forms the radiation sensitive detector element. Changing the temperature by incident radiation of the pyroelectric plate will influence charges in the electrodes. The resulting short circuit current is proportional to the temperature rate:

$$i_P = pA_S \frac{\Delta T_P}{dt} \qquad (4)$$

This pyroelectric 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 (Op Amp) as seen in figure 2 [3].

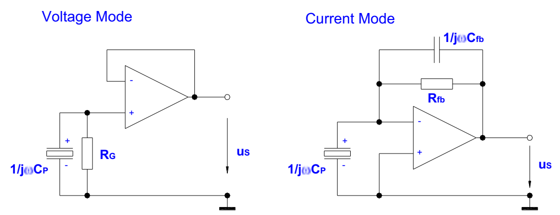


Fig. 2. Alternative preamplifier modes of pyro-electric detectors [4].

The thermopile detector is an array of n miniature thermocouple junctions connected in series as differential pairs. These differential pairs make up the cold junctions and the hot junctions (see figure 4). In fact, the hot and cold junctions are connected by two dissimilar materials with a large thermoelectric power and opposite polarities, called “Arms”, creating a Seebeck effect between the junctions. A voltage is produced, proportional to the temperature gradient between the hot and cold junctions [5].

$$V_{th} = n(\alpha_A - \alpha_B)\Delta T_S \qquad (5)$$

For thin film based thermopiles, the arm materials are antimony (Sb) and bismuth (Bi). For Silicon thermopiles, the arm materials can be alternating n-type and p-type Poly-Silicon or n-type with gold (Au) or aluminum (Al). The cold junctions are typically thermally connected to the detector package and are located around the perimeter of the substrate opening. The hot junctions are located in the center of the detector pattern and are coated with an energy absorber. The hot junctions define the active area of the detector and are suspended on a thin membrane, thermally isolating them from the rest of the package.

Fig. 3 depicts graphically the frequency dependence of the temperature change, the pyroelectric short circuit current and the open circuit thermopile voltage of a pyroelectric and a thermopile detector, respectively. Assuming a thermal time constant of about 150 ms the temperature change of the radiation sensitive element achieves a saturation value below the corner frequency of about 1 Hz and has a roll-off 20 dB/decade above. Whereas the open circuit voltage (signal) of a thermopile behaves in the same manner the short circuit pyroelectric is proportional to the derivative ΔT_S/dt. The pyroelectric current increases with the frequency with 20 dB/decade and achieves a saturation value above the thermal corner frequency.

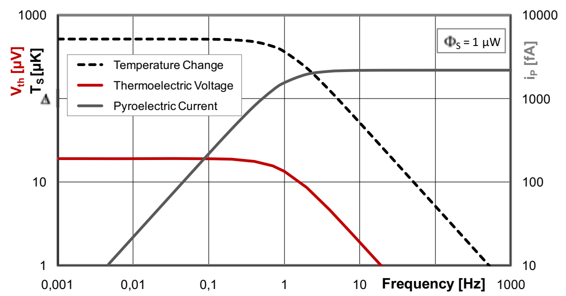


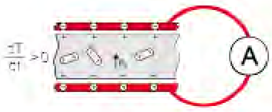
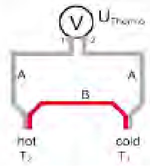
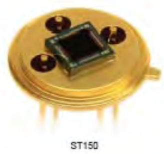
Fig. 3. Frequency dependence of the temperature change of a radiation sensitive element, of the pyroelectric short-circuit current and of the open-circuit thermopile voltage.

In table 1 the principles, basic design and samples of both pyroelectric and thermopile detectors are summarized.

Electro-Optical Properties

For the comparison of the electro-optical properties typical representatives of both the pyroelectric detector and the thermopile with a sensitive area of 1.5 x 1.5 and 2 x 2 mm² and BaF_2 window were chosen. LME-302 and LME-335 are $LiTaO_3$ based pyroelectric detectors working in voltage and current mode, respectively. ST150 and 2M are Bi/Sb thin film based and poly-silicon based thermopile detectors filled with dried nitrogen and argon, respectively.

Table. 1: Summary of the comparison of both pyroelectric and thermopile detectors

Transducer	Pyroelectric Detector	Thermopile Detector
Conversion Effect	Pyroelectric effect	Seebeck effect
Signal	Short-circuit current	Open-circuit voltage
Responsivity	Proportional to $\Delta T_S/dt$	Proportional to ΔT_S
Basic Design		
Example		

For the comparison the responsivity and the noise density were measured at 23°C in a broad frequency range of 0.1 Hz - 4.2 kHz and 0.76 Hz - 11.7 kHz, respectively.

For the measurement of the absolute responsivity at a modulation frequency of 10 Hz and a blackbody temperature of 500 K the model 563/301 from Infrared Systems Development Corporation was used. Choosing a blackbody to detector distance of about 117 nm an irradiance of about 7 µW/mm² was achieved.

The relative responsivity is measured with a high-stability super luminescent emitting diode (DenseLight DL-BZ1-CS65M5A) at a wavelength of 1635-1665 nm. The diode is modulated in a so-called multi-sinusoidal mode with frequencies between 0.1 Hz and 4.2 kHz.

The noise of the detectors at 23°C is measured with the 24 bit/204.8 kS/s 4-Input Dynamic Signal Analyzer PXI 4462 and a PXI-1042Q chassis from National Instruments. The noise density is then calculated by a software based Fourier transformation. Especially for low noise detectors an ultra-low noise preamplifier Model 5184 from Signal Recovery with a 30 dB gain was additionally used. The measured noise density (see Fig. 5) of a 10 Ω resistor at the input of the model 5184 illustrates the ultra-low noise of the preamplifier. Only at very low frequencies one can obtain an increase of the noise voltage.

In Fig. 4 the frequency dependence of the responsivity of pyroelectric and thermopile detectors is shown.

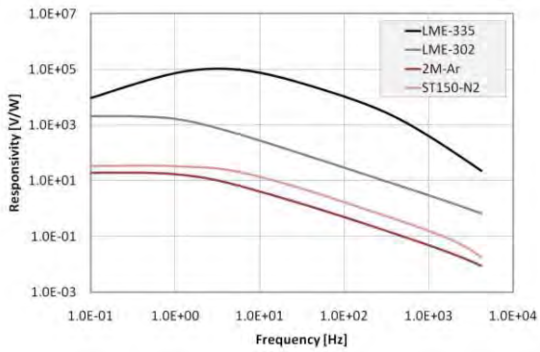


Fig. 4. Frequency dependence of the responsivity of pyroelectric (LME-302, LME-335) and thermopile detectors (ST150, 2M).

The thermopile detectors exhibit an inherently stable response to DC radiation in contrast to pyroelectric detectors. Above the corner frequency which is determined from the thermal time constants of 85 ms and 38 ms of the 2M and ST150 thermopile detectors, respectively, the response of the thermopile detectors is reduced by 20db/decade. Pyroelectric detectors feature a much higher responsivity but are characterized, in contrast to thermopile detectors, by two time constants. In the case of the voltage mode pyroelectric detector LME-302 the thermal time constant of 150 ms results in a corner frequency of about 1 Hz and a 20db/decade roll-off of the responsivity at frequencies above the corner frequencies. The electrical time constant of about 5 s results in a roll-off of the responsivity at frequencies lower than 32 mHz but is not within measured frequency range. The current mode detector is characterized by the same thermal time constant of 150 ms but features a much lower electrical time constant of 20 ms resulting in corner frequencies of 1 Hz and 8 Hz, respectively.

The absorption layer on top of the radiation sensitive elements causes an additional roll-off of the response in the kHz range. The higher the thermal resistance of the absorption layer the lower the roll-off frequency which could be clearly noticed for LME-335 and ST150.

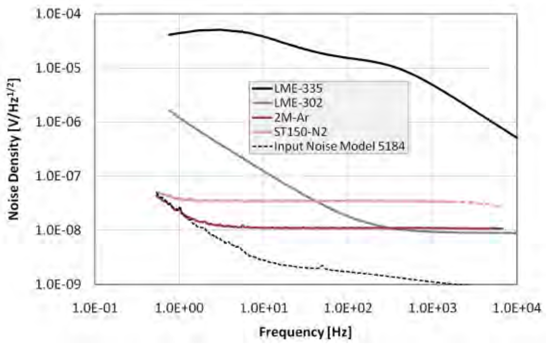


Fig. 5. Frequency dependence of the noise density of pyroelectric (LME-302, LME-335) and thermopile detectors (ST150, 2M).

In Fig. 5 the noise density of pyroelectric and thermopile detectors are compared. The thermopile detectors are distinguished by a low Johnson noise v_n in a broad frequency range cause by the internal thermopile resistance R_{th},

$$v_n = \sqrt{4kTR_{th}B} \quad (6)$$

where k is the Boltzmann constant, T the absolute temperature and B the noise bandwidth. In the frequency range below several Hz the noise density of the preamplifier dominates the measured noise and one can assume that the noise of the thermopile is flat also until a frequency of at least 1 Hz. The argon filled thermopile 2M shows a decrease of the noise density at frequencies above about several kHz because of the high internal resistance of 77 kΩ and a significant cable capacitance.

The noise density of pyroelectric detectors is dominated from different noise sources. At low frequencies until several 10 Hz Johnson noise of the high meg-ohm resistor, the current noise of the preamplifier and the temperature fluctuation noise are the dominant noise sources. In the middle frequency range until about 1 kHz the dielectric loss of the pyroelectric material dominates the noise density. Above 1 kHz the voltage noise of the preamplifier is the dominant noise source. Although the same noise sources are dominant in the same frequency ranges the frequency dependence in voltage and current mode is different due to the different preamplification of signal and noise and the different electrical time constants.

In Fig. 6 the calculated specific detectivity D* of pyroelectric and thermopile detectors are compared.

$$D^* = \sqrt{A_S\, R_V / v_n} \quad (7)$$

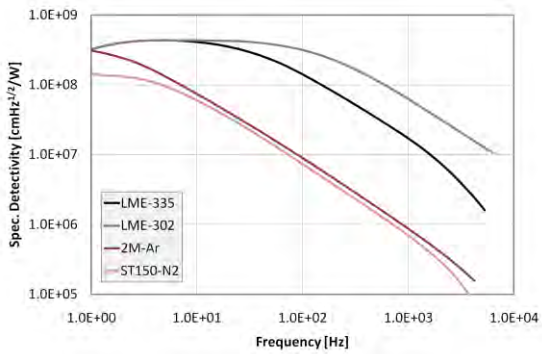


Fig. 6. Frequency dependence of the specific detectivity of pyroelectric (LME-302, LME-335) and thermopile detectors (ST150, 2M).

The pyroelectric detectors features a high specific detectivity of $3\text{-}4{\cdot}10^8$ cmHz$^{1/2}$/W in a very broad frequency range of 1-100 Hz. Only argon filled Bi-Sb thin film based thermopiles receive a specific detectivity in the order of $3\text{-}4{\cdot}10^8$ cmHz$^{1/2}$/W at very low frequencies of 1 Hz and below. The specific detectivity of silicon based thermopile detectors is lower than the Bi-Sb thin film based, especially below a frequency of 10 Hz. The reason for different behavior above about 10 Hz of the pyroelectric detectors LME-302 and LME-335 is based on the preamplifier voltage noise and the doubled input capacitance of the parallel compensated LME-335. The voltage noise of the JFET in the voltage mode source follower (LME-302) is lower than the voltage noise of the CMOS Op Amp of the current mode trans-impedance amplifier (LME-335).

Summary and Discussion

Pyroelectric and thermopile detectors are both thermal infrared transducers. Therefore responsivity and specific detectivity are high especially at low frequencies.

Thermopile detectors can be used without any chopper to detect infrared DC radiation. Further advantages are low noise and the absence of a microphonic effect. Thermopile detectors are often combined with chopper stabilized amplifiers in order to overcome the disadvantage of a very low noise voltage. As a result of their low cost thermopile detectors were applied in simple gas analysis, non-contact temperature measurements, and fire detection.

Pyroelectric detectors are distinguished by a much higher (20-40 dB) responsivity and also a higher specific detectivity. Special care must be taken for the microphonic effect. It could be reduced by a special chip mounting to a certain degree but it does not completely disappear [6]. Pyroelectric detectors are used in high performance gas analyzers, flame detection devices and scientific instrumentation. In table 2 the parameters, advantages and disadvantages of both pyroelectric and thermopile detectors are summarized.

Table. 2: Parameters, advantages and disadvantages of both pyroelectric and thermoelectric detectors

		Thermopile		Pyroelectric Detector	
Parameter		2M	ST150	LME-335	LME-302
Type		thin film based Bi-Sb	silicon based poly-silicon	$LiTaO_3$, Current Mode, compensated	$LiTaO_3$, Voltage Mode
Window		BaF_2	BaF_2	BaF_2	BaF_2
Active Area Size	mm²	2.0 x 2.0	1.5 x 1.5	2.0 x 2.0	2.0 x 2.0
Thermal Time Constant	ms	85	38	150	150
Electrical Time Constant	ms	-	-	20	4700
Responsivity (500 K, 10 Hz, 25°C)	V/W	4,1	13,9	77800	274
Responsivity (500 K, DC, 25°C)	V/W	19	34	-	-
Temperature Coefficient of Responsivity	ppm/K	-3600	-400	1000	200
Noise Density (10 Hz, BW 1 Hz, 25°C)	$nVHz^{-1/2}$	11,0	34,8	3810	12,6
Spec. Detectivity (500 K, 10 Hz, 25°C)	$10^8\ cmHz^{-1/2}W^{-1}$	0,8	0,6	4,1	4,4
Spec. Detectivity (500 K, DC, 25°C)	$10^8\ cmHz^{-1/2}W^{-1}$	3,5	2,0		
Advantage		DC & AC response, no biasing, low cost		high responsivity, high SNR	
Disadvantage		low responsivity		vibration responsive	

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