Analysis of MWIR Infrared Pyroelectric Detectors Parameters

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Abstract: - This paper outlines the analyzes of the temperature dependency of infrared pyroelectric detectors parameters at medium wavelength (MWIR). Some basic thermodynamic steady-state concepts are used to derive the equations for thermal time constant, responsivity, noise equivalent power (NEP) and detection. Certain pyroelectric materials such as TGS, $LiTaO_3$, $LiNbO_3$, $Li_2SO_4xH_2O$, $BaTiO_3$, $NaNO_2$, PVF_2, SBN and SbSi have been analyzed within the temperature range of -40°C up to 70°C. Analytically it is proven that thermal time constant decreases with increasing temperature and decreasing the thickness of the detector. Analyses have shown that the smallest response time for detector which operates at room temperature 300K was achieved for the material $Li_2SO_4xH_2O$ with value of several milliseconds, but anyway much greater then that of photon detectors. It is also shown that NEP depends directly on circuit noises voltages. In the paper are analyzed three types of noises: thermal noise, dielectric noise, and amplifier noise. The maximum possible value of detectivity to be achieved for a MWIR infrared pyroelectric detector operates at room temperature 300K was $2.12x10^8$ for $NaNO_2$.

Key-Words: - pyroelectricity, pyroelectric detectors, responsivity, thermal time constant, NEP, detectivity.

1 Introduction

Pyroelectricity is a characteristic of some materials which stimulate generation of electric dipole moment due to changes in temperature, resulting the current which is proportional to the temperature changes. Such pyroelectric materials in which the crystals are spontaneously polarized are called pyroelectrics. This evidence enables the application of pyroelectrics for detection purposes - as thermal sensors. Full pyroelectric effect can be obtained in the cases where crystal temperature changes are homogeneous along entire crystal area, otherwise, a pseudo-effect can be caused. Perfect pyroelectric materials have a similar polar axis [1]. Pyroelectrics are high frequency thermal detectors, therefore in this paper we have analyzed pyroelectric parameters at medium wavelength MWIR, 3 – 5μm. Pyroelectric thermal detector crystal must be as thin as possible in order to ensure faster temperature changes. In this way, once the faster electric signal will be obtained, the thermal time constant value of the material will be smaller. This paper introduces the analyzes of frontal detector of 5 μm thickness and 1.5 cm^2 area. Since pyroelectric crystals responds to the minimum excitations, two factors should be taken into consideration: medium temperature and incident radiation. This radiation may derive from different objects such as: warm objects, cold objects and different laser sources [3]. Pyroelectric detectors are thermal detectors which crystal internal temperature changes when the detector is exposed to a radiation. This change in temperature affects directly the change in polarization, thus changing the parameters of this detector as well.

In practice, heat conversion into electric signal is not ideal, so the signal must be amplified. Better part of systems generates different kinds of noises, so that, when the signal is amplified, the noises will be amplified at the same time. This fact should be taken into consideration too. There are three types of noises in the pyroelectric detection system: thermal, dielectric and amplifier noises [1], [6]. Thermal noises shown up due to crystal temperature changes. Dielectric materials have a resistance, therefore dielectric noises results from this resistance. We have analyzed these types of noises and introduced relevant analytical expressions.

In general, typical pyroelectric detector system consists of four basic elements [4], which are: sensor or detector, amplifier, window comparator and coupler. The schematic diagram of a typical pyroelectric detector system is shown in Fig.1.

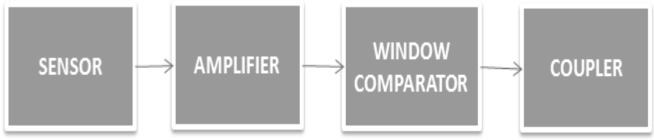

Fig. 1. Schematic diagram of a typical pyroelectric detector system

The properties of some pyroelectric materials have been shown in Table I [1], [3], [6].

Table 1.

Material	Volume specific heat c' [J/cm^3 K]	Pyroelectric coefficient p [C/cm^{2}K]	Dielectric constant ε_r
TGS	1.70	3.5×10^{-8}	35
$LiTaO_3$	3.19	1.9×10^{-8}	58
$LiNbO_3$	2.32	4.0×10^{-9}	75
$Li_2SO_4xH_2O$	0.82	1.0×10^{-8}	10
$BaTiO_3$	3.01	2.0×10^{-8}	4100
$NaNO_2$	2.016	1.2×10^{-8}	8
PVF_2	2.40	3.0×10^{-9}	11
SBN	2.34	6.0×10^{-8}	400
SbSi	2.378	2.6×10^{-7}	10^4

2 Thermal Time Constant

Thermal time constant of pyroelectric detector is the time for which incident radiation power on its input surface responds with electric signal at its output. Compared with other thermal detectors, pyroelectric detector response time is much smaller because the pyroelectric crystal does not have to reach the thermal equilibrium as in cases of thermocouples and thermistors [3]. Let C_{th} and G_{th} be the thermal capacity and conductance, respectively. Response time of the detector is given as the ratio of these two quantities named above [1], [2], [3], [6]:

$$\tau = \frac{C_{th}}{G_{th}} = \frac{c'Ab}{G_R A} = \frac{c\rho b}{4\eta\sigma T^3} \qquad (1)$$

where: c' – volume specific heat (J/cm^{3}K); c – specific heat of material (J/gmK); ρ – density (gm/cm^3); b – sensor thickness (μm); G_R – irradiative conductance (W/cmK); A – detector area (cm^2); η – emissivity of the crystal; σ – Stefan-Boltzmann constant (5.67×10^{-12} W/cm^{2}K^4); T – temperature (K).

Equation (1) indicates that thermal time constant is dependent of thickness and temperature of the detector. The Fig. 2 shows the temperature dependency of thermal time constant for some pyroelectric materials.

3 Responsivity

As discussed by [1], electrical responsivity of detector depends on two factors: thermal responsivity of detector due to incident radiation and responsivity of pyroelectric material due to temperature changes. Also thermal response depends on two factors: the radiation absorption capacity of the detector, and temperature changes due to absorbed radiation [1]. This paper provides analyzes on current responsivity R_I, and voltage responsivity R_V.

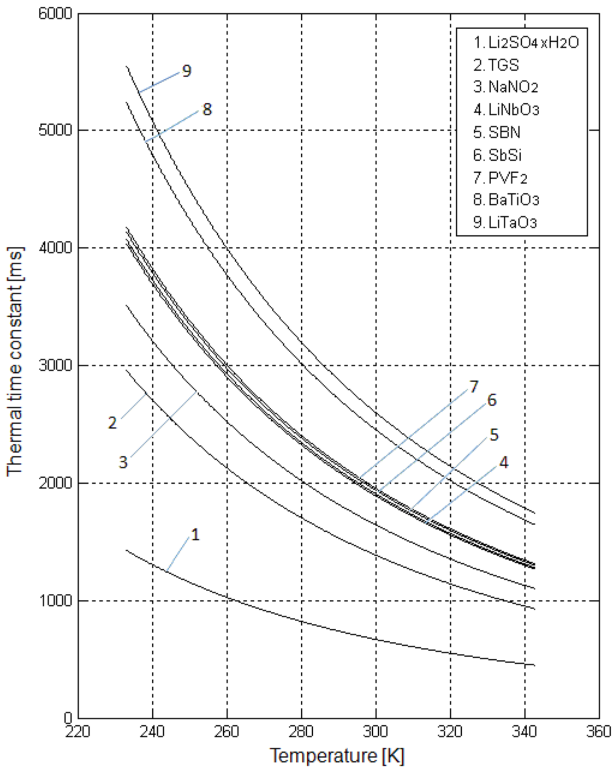

Fig. 2. Thermal time constant for some pyroelectric materials.

3.1 Current Responsivity R_I

Current responsivity R_I is the ratio of the output current flow ΔI to the input radiation power incident to detector surface P_i. The current responsivity can be calculated as [3], [4]:

$$R_I = \frac{\Delta I}{P_i} \qquad (2)$$

Pyroelectric charge ΔQ is given by:

$$\Delta Q = \Delta I = pA\Delta T = AP_S \qquad (3)$$

where p – pyroelectric coefficient of material and P_S – polarization.

Let we suppose that radiation power is sinusoidal function, therefore, temperature changes of whatever detector due to irradiation flux is given by steady-state equation as [3]:

$$\Delta T = \frac{\eta P_i}{c' b A} \frac{\tau}{\left(1+\omega^2\tau^2\right)^{1/2}} \qquad (4)$$

Substituting (3) and (4) into (2), the final expression for the current responsivity becomes:

$$R_I = \frac{p\eta\tau}{c' b\left(1+\omega^2\tau^2\right)^{1/2}} \qquad (5)$$

3.2 Voltage Responsivity R_V

Voltage responsivity R_V is determined as a ratio of the voltage generated in the detector ΔV and radiation power incident to detector surface P_i. From this definition, we have [3], [4], [10]:

$$R_V = \frac{\Delta V}{P_i} \qquad (6)$$

Generated detector voltage is given by:

$$\Delta V = \frac{\Delta Q}{C_d} \qquad (7)$$

where $\Delta Q = pA\Delta T$ is electric charge and $C_d = \varepsilon_r\varepsilon_0 A/b$ is detector capacitance.

When substituting (3), (4) and (7) into (6), we will get the final expression for the voltage responsivity:

$$R_V = \frac{p\eta\tau}{c'\varepsilon_r\varepsilon_0 A\left(1+\omega^2\tau^2\right)^{1/2}} \qquad (8)$$

In Fig.3 it is shown the wavelength dependency of the voltage responsivity for the different pyroelectric materials.

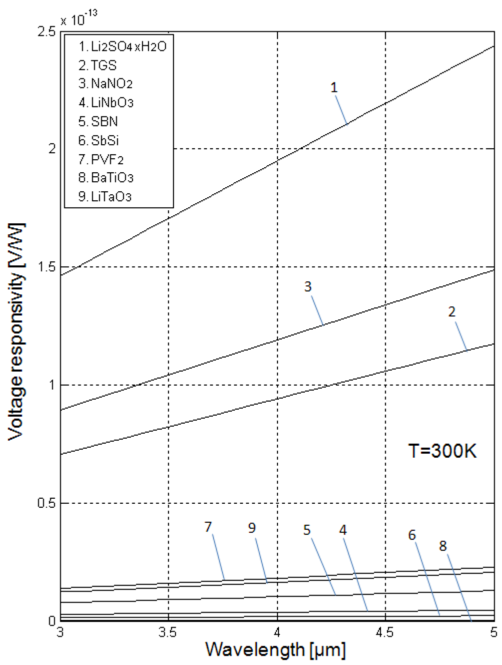

Fig. 3. Voltage responsivity for the different pyroelectric materials at room temperature 300 K.

4 Noise Equivalent Power (*NEP*)

Noise is characterized by the signal to noise ratio *SNR*, which is determined as the ratio between signal power and noise power. For detecting a signal, signal to noise ratio should be greater than unity. *S/N* ratio of the pyroelectric detector is given by the expression below [3]:

$$\frac{S}{N} = \frac{P_i}{\left(4kT^2AB\right)^{1/2}} \qquad (9)$$

where P_i - incident radiation power, k – Boltzmann constant, B – bandwidth.

Noise equivalent power (*NEP*) is the incident detector radiation power for which signal to noise ratio is equivalent to the unity, for the specific wavelength, thus minimum detectable power. Usually, *NEP* is specified for the given value of the wavelength, modulation frequency, bandwidth of the detector frequencies, temperature, and cut-off frequency. In most of the cases, infrared sensors are described by their *NEP*, using as a reference a black body at the temperature of 500 K, for cut-off frequency of 90 Hz, and for frequency bandwidth of 1 Hz, and so, *NEP* can be written as NEP(500,90,1) [7].

Noise equivalent power for the pyroelectric detector is given as a ratio of total noise voltage V_{noise} and voltage responsivity R_V:

$$NEP = \frac{V_{Noise}}{R_V} \qquad (10)$$

Now, we need to determine the total noise voltage Vnoise.

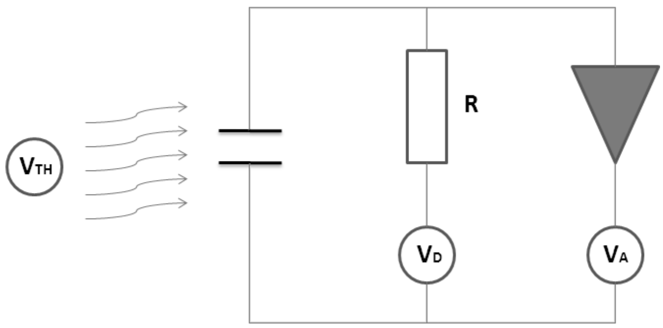

Fig. 4. Noise sources in the common detector circuit.

The major noise sources in a common detector circuit, as shown In Fig.4, are: Thermal noise, V_{Th}; Dielectric noise, V_D, and; Amplifier noise, V_A.

Thermal noise V_{Th} is generated as a result of temperature changes in pyroelectric crystal. These thermal changes are consequence of incident radiation. This noise is very small, and the smallest of three noises mentioned above. Incident radiation power that falls into detector area is given by [6]:

$$P_i = \left(4kT^2G_{th}\right)^{1/2} \qquad (11)$$

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Finally, thermal noise, as a voltage, is calculated by the expression below [6],[10]:

$$V_{Th} = R_V \frac{P_i}{\eta^{1/2}} \qquad (12)$$

Dielectric materials also have a resistance. Due to the thermal motion of electrons, in this resistance occurs a so-called dielectric noise, or Johnson noise. From Fig. 4 we can see that dielectric noise voltage is in series with a resistance, at a bandwidth of 1 Hz. Referred to the amplifier input (Fig.4) the corresponding voltage will be [2], [5], [11]:

$$V_D = \left(\frac{4kTR}{1+\omega^2\tau^2}\right)^{1/2} \qquad (13)$$

Amplifier noise V_A is the noise produced by electronic amplifier used in the detection system. According to the type of amplifier that is used, we can derive the specific amplifier noise equation. Amplifier noise can be calculated as [4], [9]:

$$V_A = \left(\frac{4kb\tan\delta T}{\omega\varepsilon_r A}\right)^{1/2} \qquad (14)$$

where tanδ – loss tangent. The values for loss tangent of the material and load resistor are 0.003 and $10^{12}\Omega$, respectively. Typical values for some types of proper amplifiers that can be used in pyroelectric sensor system are shown in Table II [6].

Table 2.

Amplifier	Frequency (Hz)	Voltage Noise ($V/Hz^{1/2}$)	Current Noise ($A/Hz^{1/2}$)
BFW II	10^{14}, 10^{15} and 10^{16}	10^{-9}	10^{-14}
XE 5886 Triode Connected	10^{14}, 10^{15} and 10^{16}	10^{-8}	10^{-15}
XE 5886 Pentode Connected	10^{14}, 10^{15} and 10^{16}	10^{-7}	10^{-16}

Now, although we found analytical expressions for the three types of noises, we can easy calculate total noise voltage Vnoise, which is given as the square sum of the three noise generators:

$$V_{Noise}^2 = V_{Th}^2 + V_D^2 + V_A^2 \qquad (15)$$

Finally, noise equivalent power is given with the expression below:

$$NEP = \frac{\sqrt{V_{Th}^2 + V_D^2 + V_A^2}}{R_V} \qquad (16)$$

In Figure 5 it is shown temperature dependency of noise equivalent power for some pyroelectric materials.

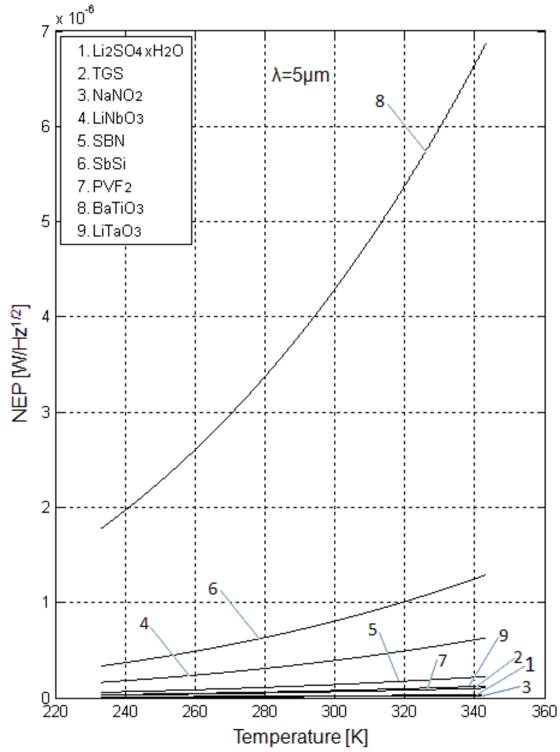

Fig. 5. Noise equivalent power (NEP) for different pyroelectric materials.

5 Detectivity *D**

Another pyroelectric sensor parameter of great importance is detectivity *D**. Value of sensor detectivity is denoted as *D*(T,f,1)*, where *T* is the temperature in degrees Kelvin, *f* is the frequency and 1 stands for bandwidth of 1 Hz. The unit of detectivity is $cmHz^{1/2}W^{-1}$. The maximum possible value of *D** to be achieved for a thermal sensor operates at room temperature 300K and viewing backgrounds at room temperature is 1.98×10^{10} $cmHz^{1/2}W^{-1}$ [5]. At a given frequency for a constant sensor thickness, *D** is given as a ratio between the square root of sensor area *A* and noise equivalent power *NEP*, which is given in (16). Thus, *D** can be calculated by expression below [1], [3]:

$$D^* = \frac{A^{1/2}}{NEP} \qquad (17)$$

In Fig. 6 it is shown temperature dependency of detectivity *D** for different pyroelectric materials at the wavelength of 5µm. Generally, pyroelectric sensors parameters values for some pyroelectric materials in the room temperature 300 K are shown in Table III.

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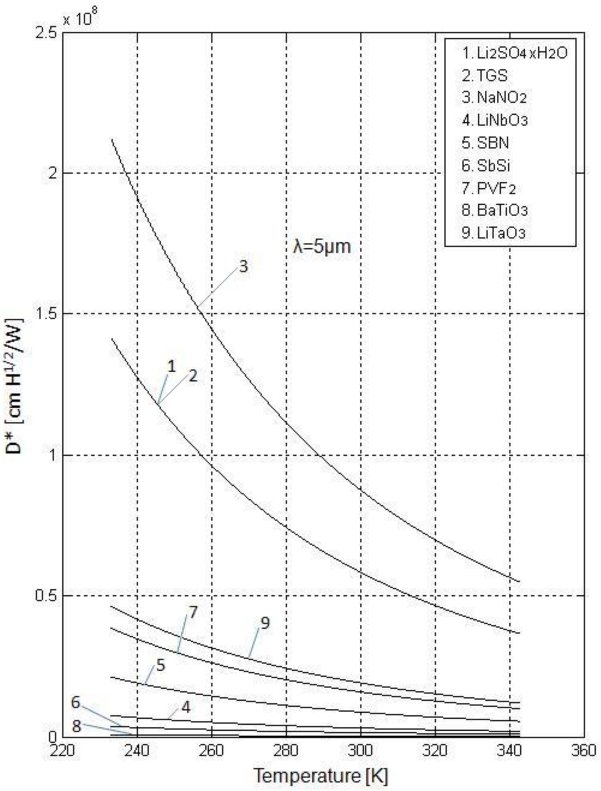

Fig. 6. Detectivity as a function of temperature for constant sensors area of 1.5 cm^2.

Table 3. Pyroelectric sensors parameters values in 300K

Material	τ [ms]	R_V [V/W]	NEP [W/$Hz^{1/2}$]	D* [cm$Hz^{1/2}$/W]
TGS	1390	$7.05x10^{-14}$	$8.658x10^{-9}$	$1.41x10^{8}$
$LiTaO_3$	2600	$1.23x10^{-14}$	$2.643x10^{-8}$	$4.63x10^{7}$
$LiNbO_3$	1890	$2.76x10^{-15}$	$1.623x10^{-7}$	$7.54x10^{6}$
Li_2SO_4 xH_2O	670	$1.46x10^{-13}$	$8.658x10^{-9}$	$1.41x10^{8}$
$BaTiO_3$	2460	$1.94x10^{-16}$	$1.774x10^{-6}$	$6.9x10^{5}$
$NaNO_2$	1650	$8.92x10^{-14}$	$5.773x10^{-9}$	$2.12x10^{8}$
PVF_2	1960	$1.36x10^{-14}$	$3.175x10^{-8}$	$3.86x10^{7}$
SBN	1910	$7.69x10^{-15}$	$5.771x10^{-8}$	$2.13x10^{7}$
SbSi	1940	$1.31x10^{-15}$	$3.329x10^{-7}$	$3.68x10^{6}$

6 Conclusion

In this paper we have analyzed four major pyroelectric sensors parameters for some different pyroelectric materials. Based on results obtained, as shown in figures (2, 3, 5, 6) and Table III, we see the impact of temperature and wavelength on the sensor parameters. Therefore, we can conclude that thermal time constant decreases by increasing temperature and decreasing the thickness of sensor. Now, briefly we will discuss the results obtained for the four parameters, for the pyroelectric sensors which operate at room temperature 300 K. The smallest response time was achieved for the material $Li_2SO_4xH_2O$ with the value of 670 ms and the largest response time was for $LiTaO_3$, 2600 ms. It is shown that voltage responsivity depends on wavelength, thickness and detector area. Voltage responsivity maximum and minimum values operate at room temperature 300K, are $1.46x10\text{-}^{13}$V/W for $Li_2SO_4xH_2O$ and $1.94x10^{-16}$ V/W for $BaTiO_3$. It was shown that *NEP* depends directly on circuit noises voltages. The maximum possible value of *D** to be achieved for a MWIR infrared pyroelectric detector which operates at room temperature 300K is $2.12x10^8$ $cmHz^{1/2}W^{-1}$ for $NaNO_2$.

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