Calibration of pyroelectric infrared detectors using a light bulb as a black body radiation source

S Pakluea\textsuperscript{1,2,3}, M Jitvisate\textsuperscript{3} and S Rimjaem\textsuperscript{1,3,*}

\textsuperscript{1}Plasma and Beam Physics Research Facility, Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Chiang Mai, 50200, Thailand
\textsuperscript{2}Master Degree Program in Physics, Department of Physics and Materials Science, Faculty of Science, Chiang Mai University, Chiang Mai, 50200, Thailand
\textsuperscript{3}Thailand Center of Excellence in Physics, Commission on Higher Education, Bangkok, 10400, Thailand

E-mail address: sakhorn.rimjaem@cmu.ac.th\textsuperscript{*} and siriwan.pakluea@gmail.com

Abstract. The pyroelectric detector is used for measuring infrared radiation. It has uniform response covering wide wavelength from 0.001 \(\mu\text{m}\) to 1000 \(\mu\text{m}\) and can measure the high-power level of radiation at room temperature operation. In this research, we calibrated the pyroelectric detector by using a tungsten light bulb as an infrared source. Properties of blackbody radiation from the light bulb are investigated. The interested properties include the spectral distribution and the relation of radiation intensity to heating temperature. The most radiation emitted from the light bulb lies in infrared wavelength. The pyroelectric detectors were calibrated against a pyroelectric Joulemeter with known responsivity. The results of this study will be applied to the measure of the radiation produced from the accelerator-base radiation source at the PBP-CMU Electron Linac Laboratory.

1. Introduction

Infrared (IR) radiation is an electromagnetic wave, whose spectrum covers the wavelength longer than visible light but shorter than millimetre regime [1-3]. Unlike visible light, IR radiation cannot be seen by human eyes and the detection requires specific receivers. There are several types of IR detectors known and used in widespread applications, \textit{e.g.}, thermopiles, bolometers, Golay cells, pyroelectric crystals, \textit{etc}. Amongst these, the pyroelectric type is one of the most popular IR detectors due to its wide range of advantages such as wide wavelength response, high signal-to-noise ratio, high-temperature stability, no requirement for cooling, and low cost [4].

Pyroelectric sensors conventionally comprise of two major components, which are the pyroelectric materials/crystals, \textit{e.g.}, \(\text{NaNO}_2\) (sodium nitrite), \(\text{LiTaO}_3\) (lithium tantalate), TGS (triglycine sulfate), and the output circuit [4,5], as shown schematically in figure 1. The radiation impinged on the pyroelectric sensor causes the temperature of the crystal element to rise. Consequently, the crystal expands and generates a polarization current \((i_s)\). This current is neutralised by the external output circuit with electrodes attached to the front and back surfaces of the sensor [6,7]. The output signals (either current or voltage) from the sensor can be amplified through the additional amplifier.

In practical radiometry, the required properties of the radiation are usually the energy or the power of the examined sources. However, the output of the pyroelectric detectors is the voltage or the current as described in the previous paragraph. Therefore, conversion from electronic signals to physical values...
is necessary [8]. This can be done by calibrating the pyroelectric detectors with the standard energy probe or another calibrated detector, such as Joulemeters. In this paper, we report the pyroelectric detector calibration method using the tungsten light bulb as an IR source and the pyroelectric Joulemeter as a calibrator. Calibration curves exhibit linear relation of the radiation energy with the detector voltage signal for all examined detectors. The aim of this study is to establish the protocol and obtain the calibration database of our pyroelectric detectors at the PBP-CMU Electron Linac Laboratory, where the accelerator-based terahertz and mid-IR source project is being proceeded. Once the radiation from the linac is produced, this protocol or its improved version is promptly applied.

Figure 1. Schematic diagram of pyroelectric detector and the equivalent circuit diagram, where \( i \) is the current generated from the crystal, \( C_D \) is the capacitance of the electrodes, and \( R_D \) is the internal resistance. \( R_E \) represents the equivalent resistance of an external circuit.

2. Materials and methods
In order to start the calibration procedure, we began by studying the type and specifications of our pyroelectric detectors and Joulemeter. There were three detectors to be examined in this experiment. All of them are made of LiTaO\(_3\) crystals, which we denoted them by the code name D1, D2, and D3. They have different thin film surface coatings made of black organic material and chromium. Different coating materials can affect the radiation intensity measurement, spectral respond and detector time respond [6,7,9]. The Joulemeter is a pyroelectric type [10], which has been calibrated and the correct responsivity (\( R_v \)) is already known. Important specifications of the pyroelectric detectors and the Joulemeter are summarised in table 1.

| Specification      | D1    | D2    | D3    | Joulemeter |
|--------------------|-------|-------|-------|------------|
| Wavelength range   | 0.1–1000 µm | 0.1–1000 µm | 0.1–1000 µm | 0.1–1000 µm |
| Energy Range       | N/A   | N/A   | N/A   | 0.06–600 µJ |
|                    |       |       |       | (High \( R_v \): 30 kV/J) |
|                    |       |       |       | 0.003–30 mJ |
|                    |       |       |       | (Low \( R_v \): 600 V/J) |
| Detector size      | N/A   | N/A   | N/A   | 7.8 × 7.8 mm\(^2\) |
| Crystal thickness  | 100 µm| 100 µm| 100 µm| N/A        |
| Coating type       | Organic black | Chromium | Organic black | Organic black |
| Model              | P1-Series | P1-Series | P1-Series | SPJ-A-8-OB |
| Company            | Molectron | Molectron | Molectron | Spectrum Detector Inc. |

Pyroelectric sensors are sensitive to the surrounding temperature. As a result, we put the detectors and all optics elements in a closed box to avoid air flow, which can cause signal drift during the
experiment. The drawing of the setup is shown in figure 2. The light from the source was transported through a circular aperture, whose radius is adjustable from about 4 mm to 37 mm. The radiation was collected by a gold-coated off-axis parabolic mirror and was focused onto the detector. The parabolic mirror has the diameter of 50.8 mm and the focal length of 152.4 mm. The chopper is required for producing pulsed radiation because our detector can measure only the rate of change in temperature. The pulse frequency was set at about 10 Hz, which is approximately the same as the repetition rate of the linac-based radiation at our facility. According to the specifications of the detectors (table 1), the detectable spectral range covers the visible region. Therefore, we first used the He-Ne laser (wavelength 632.8 nm) as a light source but no signal was detected by any detectors or Joulemeter. This result led us to choose a 100 W tungsten light bulb to represent the black body radiator instead.

Figure 2. Experimental setup for source temperature measurement and detector calibration.

The tungsten bulb requires spectral range characterisation to ensure that it can produce IR radiation in the detectors’ detectable range. By assuming the bulb to behave as a black body radiator, Planck’s distribution in equation (1) will provide the spectral information, where \( \lambda \) is the wavelength and \( T \) is absolute temperature of the radiator.

\[
I(\lambda, T) = \frac{2\pi\hbar c^2}{\lambda^5} \left( \frac{1}{e^{\frac{\hbar c}{k\lambda T}} - 1} \right).
\]  

(1)

In order to obtain the spectral distribution, the temperature of the tungsten filament has to be measured. The tungsten filament temperature can be calculated from

\[
T = \left( \frac{R}{R_0} \right)^\gamma T_0,
\]

(2)

where \( T_0 \) and \( R_0 \) are the filament’s temperature and resistance at room temperature, respectively. This non-linear relation between temperature \( T \) and filament resistance \( R \) corrects for the coiled geometry of the filament [11,12]. Therefore, the filament temperature can be calculated by measuring its resistance.

In the experiment, the light bulb was connected to a variac which is an AC transformer that gives variable voltage. The ammeter and voltmeter were connected for measuring the current \( I \) passing through and the voltage \( V \) across the filament as shown in figure 2. The resistance was calculated using Ohm’s law. By varying the voltage from 0–220 V, the temperature of the filament was changed, as well as its resistance. The parameter \( \gamma \) in equation (2) can be determined by assuming the bulb’s emitted power (Stefan’s law) to be equal to the input electrical power, hence

\[
P = IV = \sigma A T^4 = (\text{const.}) R^{\gamma / 4}.
\]  

(3)
where $\sigma$ is the Stefan’s constant and $A$ is the surface area of the radiation emission. Plotting equation (3) in logarithmic form yields linear curve and $\gamma$ can be obtained from its slope. Putting this value back to equation (2), the filament temperatures are then determined and the spectral distributions can be plotted according equation (1).

Now we have characterised the source and it is ready to be used in the detector calibration step. In real experiment, the signal from pyroelectric sensors was further amplified by amplifiers, whose gain can be adjusted. Amplified signal was then measured and recorded with the oscilloscope for later analysis. The calibration was done by recording the radiation at the same aperture size first by the Joulemeter, then by the detector. The same procedure was repeated for the varied aperture size. In the analysis, the voltage value at peak’s maximum was read and averaged over 10 pulses. The voltage responsivity ($R_v$) can be selected between 30 kV/J and 600 V/J depending on the maximum pulse energy measurement [10]. We selected high $R_v$ (30 kV/J) to measure our low pulse energy according to energy range of Joulemeter in table 1. The voltage measured from the Joulemeter can be converted to radiation energy by dividing the value by the voltage responsivity $R_v$.

3. Results and discussion

The spectral distributions of the tungsten light bulb at each selected temperature according to Plank’s radiation law are shown in figure 3. The temperature of the light bulb obtained from the measurement is 2010 K for the maximum power of 100 W, corresponding to the filament resistance of 495 Ohms. The radiation from this temperature was used for detector calibration. The radiation intensity is higher when the temperature increases and the radiation wavelength at maximum intensity ($\lambda_{\text{max}}$) decreases as the temperature increases. This result agrees well with Wein’s displacement law. It can be seen clearly from figure 3 that the radiation fraction produced from the tungsten light bulb is mostly in the IR region ($\geq 700$ nm), indicating the suitability to be used as an IR source for pyroelectric detector calibration.

Figure 3. Radiation spectra from a 100 W tungsten light bulb at different temperatures.

There are three pyroelectric detectors that have different voltage to energy conversion and amplifier circuit. Detector “D1” consists of pyroelectric sensor coated with organic-black and a self-made amplifier, whose gain can be adjusted from x10 to x200. Detector “D2” is the pyroelectric sensor with chromium coated on surface in the test box (SPH-VM-test). The test box includes a commercialised amplifier with feedback resistor that can be selected from 100 k$\Omega$ to 10 G$\Omega$. Another detector “D3” is the pyroelectric sensor coated with organic-black in the same SPH-VM-test.

Examples of voltage signal from each detector at the same pulse repetition rate and aperture size are illustrated in figure 4. The signal indicates that for the detectors D1 (figure 4(a)) and D2 (figure 4 (b)), the time response of the detector is fast enough to measure the radiation pulse at this frequency because the whole pulse is observed, with the duty cycle of 0.4 and 0.3, respectively. For the D3 detector (figure...
4(c)), the measured duty cycle is 1.0, which means the full pulsed may not be observed. Thus, this detector is probably unsuitable for the frequency higher than 10 Hz. The time response of the detector depends on both amplifier circuit and coating material of the pyroelectric sensor. The organic-black surface has slower thermal time and electric response but measures higher signal than the metal-coated surface due to its higher light absorbance (about 40% higher) [7]. The evidence can be seen clearly from figure 4(b) and (c), where the amplifier sets were identical. The signal acquired from the chromium coated sensor (figure 4(b)) has better time response but lower magnitude than the organic-coated one (figure 4(c)), resulting from reflection loss. The signal from the Joulemeter (figure 4(d)) also shows slower time response due to its organic-black surface sensor.

![Figure 4](image-url)  
**Figure 4.** Radiation signal from the D1 (a), D2 (b), D3 (c) pyroelectric detector and the signal from Joulemeter (d) at the same pulse repetition rate and aperture size.

Increasing amplification gain allows measuring signal with lower magnitude. From the result, we found that the detector D1 can amplify the signal to have the maximum peak voltage in a range of 1 to 10 V for the gain range of x10 to x200. The maximum peak signal from the D3 and D2 detector are 60 mV and 35 mV, respectively, for the load resistor of 100 kΩ and 10 GΩ. The voltage-to-energy conversion of the three detectors are shown in figure 5. It is clear from the calibration curves that the pulse energy is linearly proportional to the maximum peak voltage. Fitting the data allows us to construct the calibration equation in the form of  

\[ \text{Energy} \ [\text{J}] = a \ [\text{J/V}] \times \text{Voltage} \ [\text{V}] \]

where \( a \) is the conversion factor obtained from the slope of the linear fits. The energy of the radiation pulse is maximum around 13 \( \mu \text{J} \), which is when the aperture is most widely open.

The D1 detector set can amplify the signal to have the highest voltage compared with other detectors, indicating that our self-made amplifier has the best performance amongst the tested systems. These results show the possibility of using this calibration protocol for our future accelerator-based radiation.
However, there are still some parts that require improvement, for example, we need to add some computer controller to switch between the pyroelectric detector and the Joulemeter in the calibration experiment since the access to the accelerator hall is not permitted during operation.

![Figure 5. The calibration curves of the (a) D1, (b) D2, and (c) D3 pyroelectric detectors.](image)

### 4. Conclusion
The pyroelectric detectors were calibrated by using the light bulb as a black body radiation source. The tungsten light bulb used in the calibration has the maximum power of 100 W. The radiation spectrum covers the wavelength from about 0.3 µm to 15 µm, with most part in the IR region, having its maximum intensity at the wavelength of 1.44 µm. The pyroelectric Joulemeter was used to convert the voltage signal to radiation energy, with the voltage responsivity of 30 kV/J. From the results, we found that the organic black coated pyroelectric detector with the self-made amplifier has the highest voltage to energy conversion. The detector with organic-black coating on the sensor surface has slower time response than the metallic surface coated sensor but the measured intensity is higher due to higher absorptance.

### Acknowledgments
This research work was partially supported by Chiang Mai University and the Thailand Center of Excellence in Physics (ThEP-61-EQP-CMU1). Furthermore, S. Pakluea would like to acknowledge the scholarship support by the Science Achievement Scholarship of Thailand (SAST).

### References
[1] Rogalski A 2011 *Infrared Detectors* (Boca Raton: CRC Press)
[2] Rogalski A 2003 *Prog. Quant. Electron* 27 2
[3] Rogalski A 2002 *Infrared Phys. Technol.* 43 3
[4] Porter S G 1981 *Ferroelectrics* 33 1
[5] Roundy C B and Byer R L 1973 *J. Appl. Phys.* 44 2
[6] Molectron Corporation 1981 *Molectron Application Note: P1-Series Pyroelectric Detector* (Sunnyvale: Molectron Cooperation)
[7] Tiffany W B 1981 *Molectron Application Note: The Amazing Versatile Pyroelectric* (Sunnyvale: Molectron Cooperation)
[8] Gentile T R, Houston J M, Eppeldauer G, Migdall A L and Cromer C L 1997 *Appl. Opt.* 36 16
[9] Blevin W R and Geist J 1974 *Appl. Opt.* 13 1171
[10] Spectrum Detector Inc. 2019 SXJ-A: Analog Joulemeter Online: https://www.photonicsonline.com/doc/sxj-a-analog-joulemeters-0001
[11] Brizuela G and Juan A 1996 *Am. J. Phys.* 64 819
[12] Dryzek J and Ruebenbauer K 1992 *Am. J. Phys.* 60 251