How To Measure Far Infrared And THz Radiation

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05/11/2012

Abstract

Our experiment aims to measure Far Infrared and THz radiation. It was held in the LAL labs, supervised by Dr. N.DELERUE. During the four half-days attendance, several issues(detection, amplification, reading results ..) have been studied.

1 Physical Overview

Infrared radiations are electromagnetic radiation of wavelength in the range of $0.74\mu m$ to 1 mm, and this corresponds to a frequency range of approximately 0.3 - 405 THz. In real life, Infrared radiations are of various origins: Solar (thermal energy by fusion on the sun), Body temperature, Black body at room temperature.

We are not interested in all of the above mentioned origins now, what we have studied was the Smith Purcell radiation (Far IR range $10\mu m$ to 1 mm)originated from the passage of an electron beam upon a metal grating, discovered by Smith and Purcell in 1953(Introduction to Smith-Purcell radiation , Nicolas Delerue-LAL(CNRS and Universit de Paris-Sud)). Nowadays, one of the methods of measuring the longitudinal profile of an electron bunch is studying SPR. For this purpose, two types of IR detectors could be used: Thermopiles and Pyroelectrics after concentrating the signal by either CPC Compound Parabolic Concentrators or OAP Off Axis Parabolic Mirrors, concentrated signals are then amplified by OP-AMP operational amplifiers and then read using ADC Analog-to-Digital Converters.

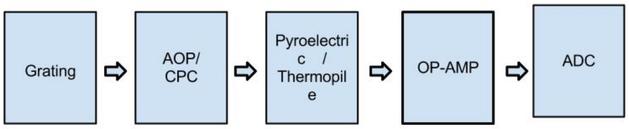

Figure 1: Experimental Setup

Figure 2: ZTP-135S Thermopile (Farnell)

Figure 3: SPH-series:Discrete Pyroelectric Detectors (Spectrum Detector Inc.)

1.1 What is a Thermopile!? And how it works?

Thermopiles are groups of thermocouple elements connected together. A thermocouple consists of two different material conductors, one put at a reference temperature (e.g ice bath) and their contact point on the target we want to study. The temperature gradient between these two points creates a potential difference △V.

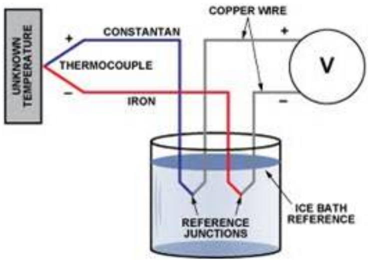

Figure 4: Thermocouple

This is called the "thermoelectric effect" which is built on three effects:

- Seebeck effect: is the conversion of temperature differences directly into electricity .
- Peltier effect: is the presence of heat at an electrified junctions of two different metal.
- Thomson effect: is the combination of both upper effects, where a current carrying conductor put at two different temperatures has the probability to emit or absorb heat depending on the material.

1.2 Pyroelectrics

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 thus temporary voltage is produced. Such pyroelectric materials in which the crystals are spontaneously polarized are called pyroelectrics.

1.2.1 How does a pyroelectic device function?

The change in temperature when light radiation (UV, IR, THz) is applied to a thin pyroelectric crystal modifies the positions of the atoms slightly within the crystal structure, such that the polarization of the material changes. This polarization change gives rise to a voltage across the crystal. If the temperature stays constant at its new value, the pyroelectric voltage gradually disappears due to leakage current (the leakage can be due to electrons moving through the crystal, ions moving through the air, current leaking through a voltmeter attached across the crystal, etc...)

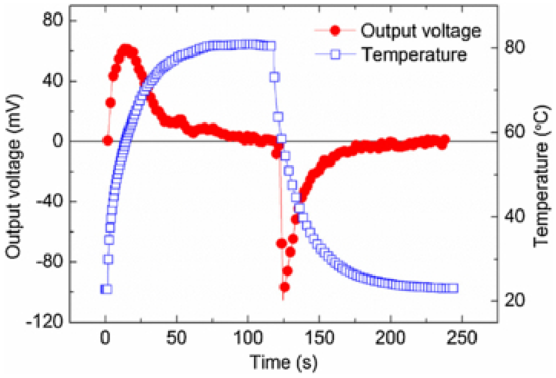

Figure 5: Variation of temperature and voltage as a function of time

1.2.2 Comparison between thermoelectric and Pyroelectric

- For Pyroelectric devices:

-Advantages:
a-Sensitive
b-Fast response time
-Disadvantages:
a-The whole crystal is changed from one temperature to another, and the result is a temporary voltage across the crystal.
b-Low detectivity

- For thermoelectric devices:

Advantages: a-One side of the material is kept at one temperature and the other side at a different

temperature, and the result is a permanent voltage.
b-Large temperature range response
Disadvantages:
a-Corrosive (metal)
b-Complexity (high errors)

2 More Into Details:

2.1 parameters:

• Sensitivity S (Thermo) or voltage/current Responsivity R_v, R_I (Pyro): measured in (V/W ,A/W)is defined as the ratio of output voltage/current to input power: S=Y/X ; Y=output voltage/current (Volts,Amperes), X=input power (Watt).

• Time constant τ: measured in seconds is the time taken by the detector to raise its output when subjected to a sudden constant radiation.
• Noise Equivalent Power NEP: It is the radiant flux in watts necessary to give an output signal equal to r.m.s noise output from the detector.
• Detectivity D: The Detectivity (cm.$Hz^{1/2}$ / W) indicates the signal to noise ratio of a detector when the incident power is 1 W. It is written as: NEP/$A^{1/2}$, where A is the active area of the detector.
• Output Impedance R' (Ohms Ω)

2.2 Calculations : Incident signal $Z = 1$ nJ/cm^2

• Thermopile: HMS J21 (HEIMANN Sensors)
S=27 V/W
D= 8.7 10^7 cm $Hz^{1/2}$/W
$\tau=10^{-2}$ s
A=1.44 10^{-2} cm^2
so X= (Z*A)/τ
$\Rightarrow$ X=1.44 10^{-9} W
S=Y/X $\Rightarrow$ Y=39 nV
(A small output signal !!)

•Pyroelectric:Model 404 VM(ELTEC)
R_v(voltage responsivity)=50 V/W

D=3.4 .10^8 cm $Hz^{1/2}$/W
A=3.2 10^{-2} cm^2
τ=1 ms
so X=3.2 10^{-8} W
Y=1.6 10^{-6}V
R'=6.2 KΩ
R_IR'=R_v $\Rightarrow$ Iout=1.12 fA

It is clear from the above calculations that we have small output signals that could not be read, so our new mission is to try to amplify such signals in various techniques: CPC, OAP, Op-Amp.

2.3 CPC (Compound Parbolic Concentrator)

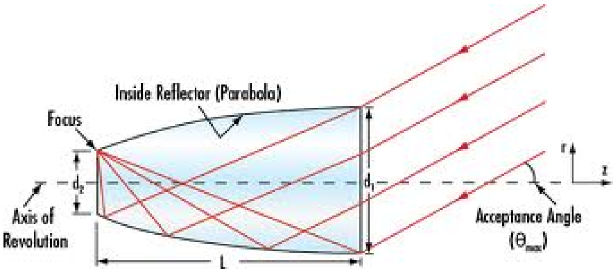

Figure 6: CPC

CPC is a class of parabolic concentrators that consist of rotated parabolic sections which have a concentration factor of $1/\sin(\theta_a)$, where θ_a is the acceptance angle: one-half of the angle within which the reflectors direct all the light incident onto the aperture down to the receiver.
The optical principle of a reflecting parabola is that all rays of light parallel to its axis are reflected to a point. CPC s are mostly used in solar cells to concentrate rays coming from the sun.

2.3.1 CPC Concentration with thermopile

Since at the exit of the aperture is the detector, then the gain of the CPC is obtained by only replacing the active area of the detector by the input area A_{in} of the CPC. Considering one CPC of input radius of 11 mm(A_{in}= 3.8cm^2) and output radius of 1.5 mm A_{out}=0.07cm^2, then my output signal from the above considered thermopile would be Y=10.3 μV. But we should keep in mind that when A<A_{out} of the aperture, then to get a precise value of Y, we should multiply the above Y by the ratio of A/A_{out} since in this case not all the signal reflected by the CPC will be detected by the detector, so finally we will get Y=2.1μV. Concentration=Y_{CPC} /Y_{thermo} ~54 times.

2.4 Off Axis Parabolic Mirrors OAP

OAP mirrors are mirrors that are free from spherical aberrations, and thus focus the parallel beam to a point. Parabolic mirrors are the most common type of aspherical mirrors used in optical instruments.

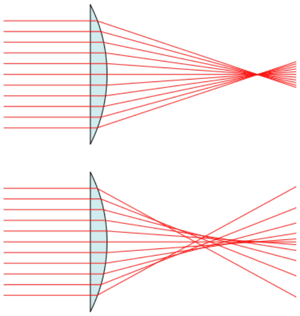

Figure 7: OAP

In reality a perfect lens focuses all incoming rays to a single point on the optical axis, but in real lens with spherical surface focuses different rays to different points along the optical axis, depending on the radial position of each incoming ray. The second figure shows the aberration of a given lens. They are mostly used in Expanders/Collimators: For which they are used to either expand or reduce the laser beam diameter, Radiometers etc...

2.4.1 Between OAP and CPC :

Advantages:
Off Axis describes less aberration, Mirror
For CPC we have Less background. Disadvantages:
For OAP, more expensive than other mirror types.
For CPC, Less efficient depending on the ratio of A_{out} to A.

2.4.2 OAP mirror Concentration with Pyroelectric

As mentioned above the same method is used except here we don't have efficiency due to area variation since the rays are totally concentrated at a certain point.Here we have to consider the A_{in}=area of the mirror of raduis 50 mm which is 78.54 cm^2 and as the response time of the detector used (404 VM) is given by 1ms then the output voltage is 8 10^{-5} V. Concentration=~49.1
Now, even placing one of the above mirrors we also obtain a small signal, so now a new amplification way is introduced by placing op-amp(s) after detectors.

2.5 OP-AMP :

2.5.1 Definition & Types :

An operational amplifier (op-amp) is a DC-coupled high-gain electronic voltage amplifier with an input and output signals. An op-amp produces an output voltage that is typically hundreds of thousands of times larger than the voltage difference between its input terminals. We have two types of op-amp(s):
- Non-Inverting OP-AMP (Figure 8)
- Inverting)P-AMP (Figure 9)

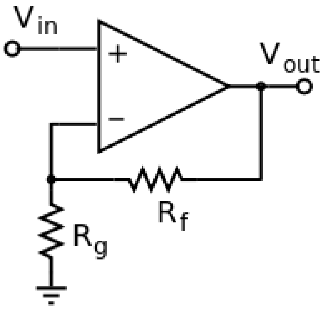

Figure 8

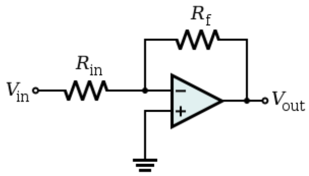

Figure 9

2.5.2 Gain of OP-AMP

The gain equation is given by:

$$V_{out} = G \times V_{in}, \qquad (1)$$

where here V_{in} is the Y obtained from one of the above mirrors, V_{out} is the output signal from the op-amp and G=gain.
Planning to get a V_{out}=1V and Considering R_g=1KΩ op-amp.
- Non-inverting with thermopile ($V_{in} = 2.1\mu$ V):
$G=1+R_f/R_g=4.8\ 10^5 \Rightarrow R_f \sim 480$ MΩ. Since R_f is large to be found, we can manage to put a group of Op-Amp(s)in series.
- Inverting Op-AMP with pyroelectric($V_{in}=8\ 10^{-5}$ V):

Our V_{in} here is negative.
$G=R_f/R_{in} = -V_{out}/V_{in}=12{,}500 \Rightarrow R_f=12.5$ MΩ.
So, by using an R_f of 12.5 MΩ we can achieve the amplification needed.
Now, how to read our RESULTS ?!

2.6 ADC

2.6.1 Definition & Work:

An analog-to-digital converter is a device that converts the input physical quantity to a digital number that represents the quantity's amplitude. The conversion involves quantization of the input, so it introduces a small amount of error.

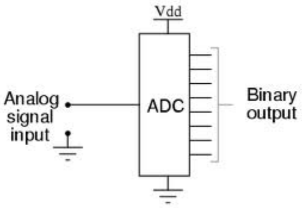

Figure 10 : ADC

2.6.2 DT5740 (CAEN)ADC with thermopile

DT5740 with 12 bits and an input range of 0-5 V, has a resolution of $\delta V=V_{max}/2^n=1.2\ 10^{-3}$ V where V_{max}=5 V and n=number of bits =12 bits. The output result is the following 001111111111, this gives an output value of 0.625 V $< V_{out} <$ 1.25 V
Error estimation:
Starting from the ADC error above and moving backward in calculation by dividing it by each gain, we obtain an error on the incident input signal
$\delta_s=2.1\ 10^{-5}$ nJ/cm^2.

2.6.3 PCIe-18AI32SSC1M (General Standars Corporation) with pyroelectric

PCIe-18AI32SSC1M with 18 bits and an input range of 0-10 V has a resolution of $\delta V=3.8\ 10^{-6}$V. The outputresult is the following 111111111111111111, this gives an output value of 0.999996 V $< V_{out} <$ 1 V.
Error estimation:
Same method as above, we get $\delta_s=1.6\ 10^{-9}$ nJ/cm^2

3 Conclusion:

Our goal was to measure the input SPR signal and it's obvious from what we have mentioned above that it was not that trivial. Using detectors only was not enough, the signal should has been amplified and this was what we have done using all the above instrumentation that has introduced different error types.

References

[1] Victoria Blackmore, Thesis: Determination of the Time Profile of Picosecond-Long Electron Bunches through the use of Coherent Smith-Purcell Radiation JAI-THESIS-2009-01

[2] Wikipedia

[3] Introduction to Smith-Purcell radiation , Nicolas Delerue-LAL(CNRS and Universit de Paris-Sud)