P473 Term paper:
Bolometers in astronomy

Dwaipayan Paul
Roll No.-1811064
Int. Msc., SPS

Introduction

A bolometer is basically a device that measures power of electromagnetic radiation from the surroundings by converting it into a measurable quantity like voltage or current. It was invented by Langley in 1878 to study radiation from the sun. There are types of bolometers which will be discussed below in categories.

Bolometers have been used in wide range namely, far-infrared (FIR), sub millimeter (Sub mm) and millimeter (mm) wave astronomy. They are used for any kind of radiation, it may be photons, ionising or non-ionising radiations, or form of mass and energy which unknown, like the dark matter. They are mostly sensitive to wavelengths between 200 m, for cases of stressed photo conductors, to 2-3 mm. It has been nowadays used in large submm/mm telescopes. The submm/mm range holds a great significance in the field of astronomy, hence bolometers have great applications in this field.

SCUBA camera[1] is a bolometer array operated at JCMT (James Clerk Maxwell Telescope) and Boomerang instrument. Both of the instrument have a lot of contributions in astronomy[2]. SCUBA came useful in studying star formation, molecular clouds and discovery of vast debris disks of cold dust[3].

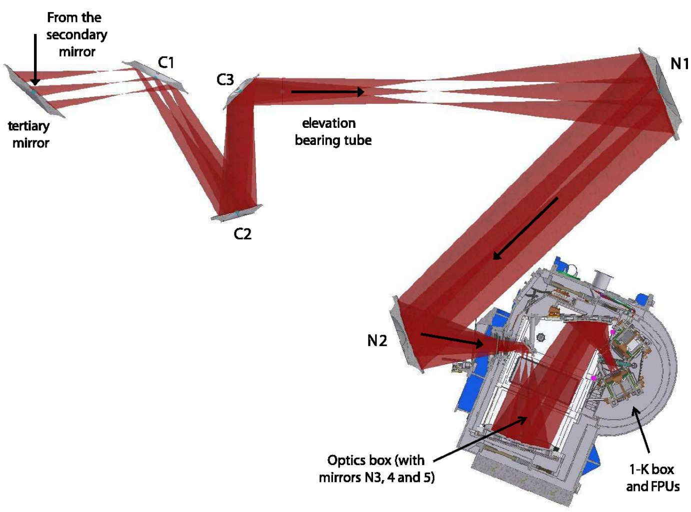

Figure 1: SCUBA-2 camera in James Clerk Maxwell Telescope

Theory

Principle

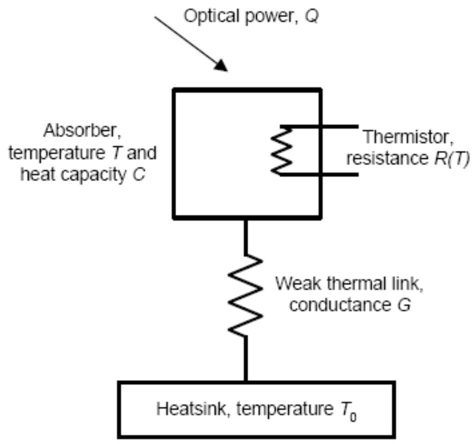

Figure 2: SCUBA-2 camera in James Clerk Maxwell Telescope

Here, figure 2 shows a schematic diagram of a bolometer. It has a absorber, which takes in the radiation (generally a layer of metal), and its connected to a heat sink or reservoir through a weak thermal link. The working is as follows: The absorber, say of heat capacity C, absorbs temperature and hence increases its temperature. The increase in temperature is proportional to the absorbed power. The weak thermal link (of conductance G) transfers the heat energy to the sink, which is kept at a fixed temperature T_o. The temperature rise which is ΔT, and is equal to the ratio of energy of incident radiation E and heat capacity C,

$$\Delta T = Final - Initial = T - T_o = \frac{E}{C}$$

until the power flowing to the sink is equal to power of incident radiation. The rise of temperature is measured to get the corresponding energy of the radiation. Now generally, this is calculated using a biased circuit as shown in the figure.

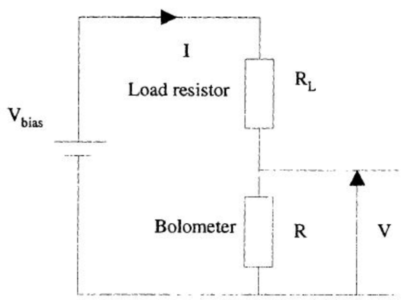

Figure 3: Bolometer bias circuit [4]

V_{bias} is the bias voltage, R_L is the load resistance. They give rise to the current I. The bias power is given by,

$$P_{bias} = V_{bias} I$$

where I is constant. The bolometer temperature for constant bias power will be,

$$T = T_o + (P_{sig} + P_{bias})/G$$

where P_{sig} is the power of the signal captured by the telescope. As seen in the above figure, the bolometer also provide a resistance R, across which voltage V is measured. This resistance depends on the temperature rise of the bolometer. The voltage can be amplified, which is helpful for the weak signals. Nowadays the semiconductors are used as absorbers in bolometer for greater sensitivity.

Noise equivalent power

Noise equivalent power or NEP is one of the performance determining parameters. NEP is defined as the power absorbed that produces a signal to noise ratio of unity at the output. The lower the NEP, the better is the performance of the bolometer. It considers the contribution from the thermal background, which is ideal. Generally,

$$NEP^2 = NEP^2_{detector} + NEP^2_{background}$$

The detector noise comes from two sources-

1. Johnson noise:
   It arises due to agitated movement of the electrons. The formula for $\mathrm{NEP}_{Johnson}$,

   $$NEP^2_J = 4k_BTR/S^2$$

   where, k_B is the Boltzmann constant, T is temperature and S is the responsivity/output of the device (V/W).

2. Phonon noise:
   The exchange of energy between a thermal mass and the surrounding environment, is quantized in the form of phonons. This noise arises from the trasport of energy from absorber to heat sink. The formula for NEP_{Phonon},

   $$NEP^2_P = 4k_BT^2G$$

   where G is the conductance of the thermal link between absorber and the heat sink.

3. Photon noise:
   It is caused due to random fluctuations in the absorption rate, given by,

   $$NEP^2_{PH} = 2Q(h\nu_0 + \eta\epsilon kT)$$

   where ν_0 is the central frequency of the bandwith $\Delta\nu$, Q is the absorbed power from the incident radiation, T is background radiation temperature, η is overall transmission of the system, ϵ is emissivity of background. The absorbed power Q is given by,

   $$Q = A\Omega B(\nu_0, T)\eta\epsilon$$

   where A is the primary area of the telescope, Ω is the beam solid angle, $B(\nu_0, T)$ is the Planck function.

Therefore, overall NEP is given by the summation of all the contributors,

$$NEP^2 = 4k_BTR/S^2 + 4k_BT^2G + 2Q(h\nu_0 + \eta\epsilon kT)$$

To get lower NEP, the values of R, G and Q should be decreased and value of S should be increased. The operating temperature T should also be decreased, which increases the sensitivity of the device.

Thermal time constant

Thermal time constant or τ is also a performance parameter. It is the response time to the incident radiation, and is given by the ratio of heat capacity of the absorber to the thermal conductance of the thermal link,

$$\tau = \frac{C}{G}$$

The more the G, the less is τ, which means faster response but comes with a cost of more NEP. Hence we have to select an value to optimise the performance.

Ideal performance

We discussed about the resistance of the bolometer in the bias circuit. The temperature dependence of resistance is given by:

$$R = R^{*}exp(T_g/T)^{1/2}$$

where the R^* and T_g are intrinsic properties of the material. The temperature co-efficient of resistance is given by,

$$\alpha = \frac{T}{R}.\frac{dR}{dT}$$

Increasing α will increase its sensitivity. The performance of an ideal bolometer can be characterised by the parameters: Bias parameter, Material parameter and Loading parameter.
Bias parameter (ϕ) is the characteristic of the circuit given by,

$$\phi = \frac{T}{T_O}$$

Material parameter (δ) is the characteristic of the material, which is measure of the change in resistivity with temperature.

$$\delta = \frac{T_g}{T_o}$$

Loading parameter (γ) is the measure of the power of incoming radiation,

$$\gamma = \eta\frac{Q}{GT_o}$$

Categories

Types of bolometers are:

I. Semiconductor bolometers

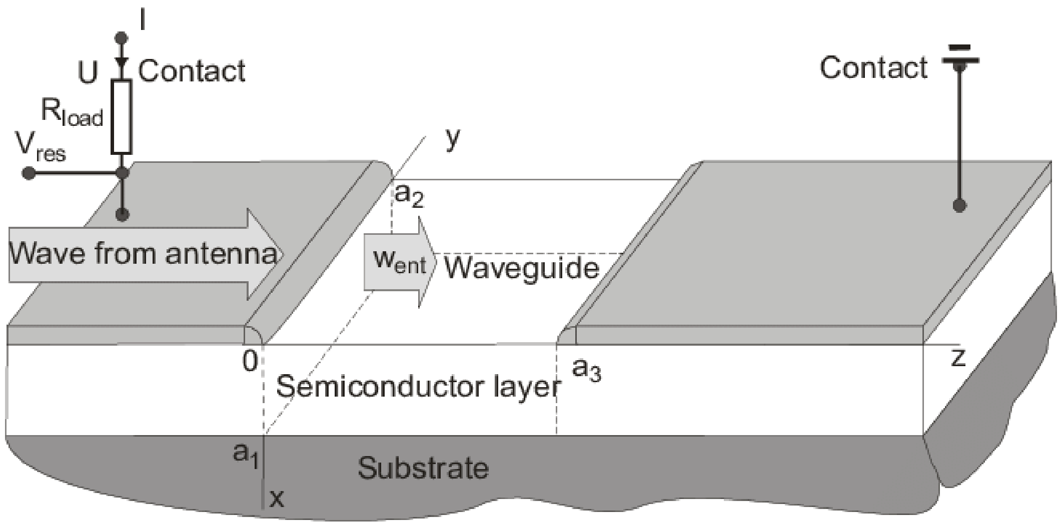

Figure 4: Semiconductor bolometer configuration

In the above figure a basic schematic configuration is given. They have a semiconductor based resistance thermometer (rise in temperature calculated by the circuit), its absorber is generally a metal coated dielectric. The SCUBA bolometers is one of the examples. It uses NTD (Neutron Transmutation Doped) germanium, attached to the center of bismuth coated sapphire substrates. The arrangement is held by glass rods.
Spider-Web bolometer is also an example. It also uses NTD germanium, in the center of silicon nitride web which used as an absorber. NTD germanium is used because of its wide range of resistivity values.

II. Superconducting TES devices

TES or Transition Edge Sensors are cryogenic energy sensors which works on the strong dependence of resistivity with temperature in transition region (normal - superconducting states). Here is a resistance vs temperature graph,

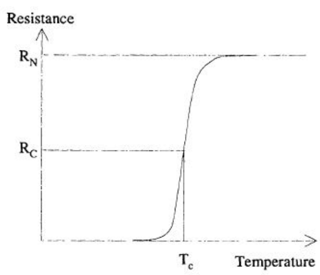

Figure 5: Resistance-temperature dependence[4]

Here, we can see the slope is very high during the transition, starting from the critical temperature T_c. Therefore a small change in temperature will result in larger change in resistance, all we have to do is keep in transition region using appropiate bias voltage.

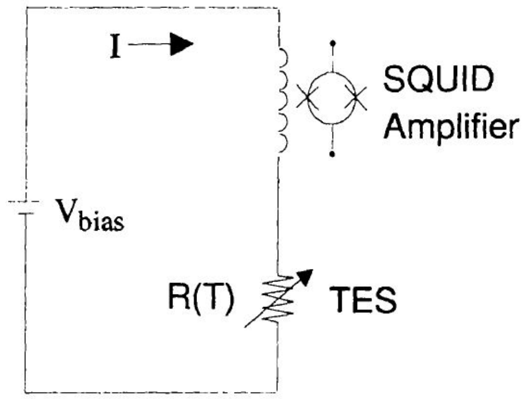

Figure 6: TES bias circuit [4]

Here is the bias circuit. The temperature changes the resistance which change the bias current I, which is then measured using SQUID or super conducting quantum interference device amplifier.

III. Silicon bolometers

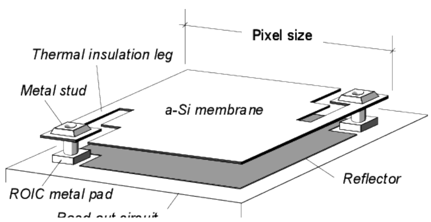

Figure 7: Schematic of the amorphous silicon microbolometer pixel

Pop-up detectors or PUDs is an example. They use ion-implanted silicon thermometers , in a linear array structure. They have been developed by NASA Goddard for CSO and SOFIA observatory. The device have good electro thermal properties.

Design

I. First bolometers

Langley's bolometer used steel, platinum foil strips which was covered with lampblack. The arrangement of Wheatstone bridge was made, of which two branches where strips and used a sensitive galvanometer connected to a battery. The temperature change in the strips due to incident radiation resulted in change in resistance.

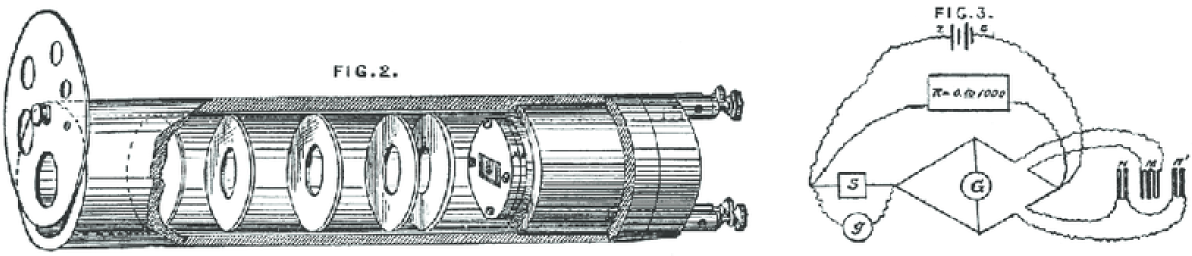

Figure 8: Langely's bolometer [5]

II. TES functioning

In TES (discussed above), the total power is given by :

$$P_{total} = P_{bias} + P_{background}$$

As the incoming radiation power increase, the temperature of the bolometer increases. This increases the resistance R and we know that,

$$P_{bias} = V^2/R$$

Now in the transition region, the P_{bias} decreases with increase in R. This compensates the increase in $P_{background}$, keeping the total power constant. This is called Electrothermal Feedback (ETF). Decrease in P_{bias} suppresses the Johnson noise, thus helps in improving NEP. It also speeds up the detector by decreasing the response time. But if $P_{background}$ increase too much it will cause P_{bias} to reach 0. Then the bolometer is said to be saturated.

III. Practical Design

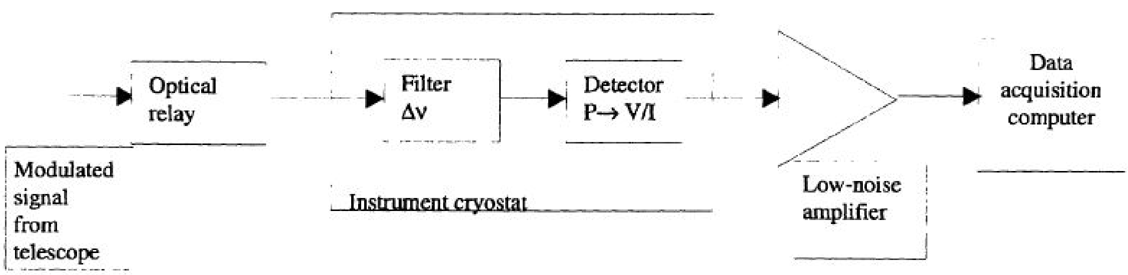

Figure 9: Working of a practical bolometer [4]

Above is the basic flowchart of its working.
Typically, heat capacity of the material are proportional to T in case of metals and T^3 in case of

dielectrics. The NEP are proportional to $TC^{1/2}$. Therefore, intrinsic NEP are proportional to $T^{3/2}$-$T^{5/2}$. The operating temperature is minimised to get a lower value of NEP.
In submm wave astronomy, optical coupling is used to avoid size problems. The bolometer is kept in a cavity and coupled with incident bram using a conical horn.

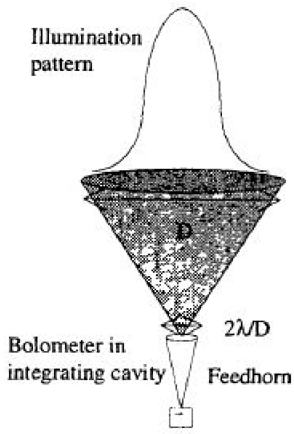

Figure 10: Feedhorn-coupled bolometer [4]

In bolometric devices, the electronics used are made in such way that it produces less noise. Cooled JFET amplifier used in semiconductor devices are a good example. The JFET is cooled to minimise gate current noise. Moreover superconducting wiring is done to avoid noise and minimise heat leaks.
There are other issues which are to be addressed:

- Stray light: Any unnecessary form of energy is called stray light. This adds up to photon noise hence affecting the performance. Visible or near IR photons need to be avoided in case of sub mm astronomy.
- Grounding: The electronics involving bolometer must be ground properly.
- External fields: Proper shielding is done to avoid noise contributions any other magnetic field.
- Microphonics: It arises due to the relative motion of the internal wiring or apparatus with respect to the bolometer. Motion of the wiring adds current due to change in capacitance to the ground. It is reduced by using rigid structure, and reducing the length of the wire.

Research

- SCUBA or Submillimetre Common-User Bolometer Array, a semiconductor bolometer, has been discussed above. It is mounted on Nasymth platform of the JCMT.
- SHARC or Submillimetre High-Angular Resolution camera was installed on CSO telescope on Mauna Kea, operating on wavelengths of 350 and 450 *micro* m. Similiarly there are MAMBO (MPIfR bolometer arrays) for IRAM 30m telescope and BoloCAM (Bolometer Camera).
- Satellites like Herschel and Planck satellites will get spider web bolometer arrays for further study. SPIRE is the bolometer array on Herschel which will be operating at 250, 300 and 500 micro m.

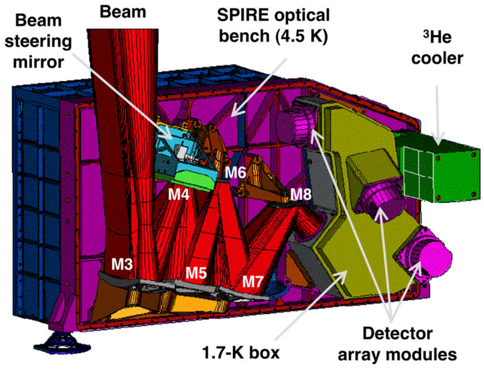

Figure 11: Diagram of SPIRE on Herschel [6]

- TES devices are being developed with multiplexed SQUID amplifiers. It will use silicon micromachining and thin film depository technique, which will help in constructing large format arrays of many pixels. SCUBA-2 is an example, which is much faster than the SCUBA and can scan large areas of sky.
- Nowadays researches are going to make coupled telescopes, which are really expensive to build. Planar lithographed antennas are developed for SIS which is an example.

References

[1] W. S. Holland, E. Robson, W. K. Gear, C. R. Cunningham, J. F. Lightfoot, T. Jenness, R. J. Ivison, J. A. Stevens, P. A. Ade, M. J. Griffin, *et al.*, "Scuba: a common-user submillimetre camera operating on the james clerk maxwell telescope," *Monthly Notices of the Royal Astronomical Society*, vol. 303, no. 4, pp. 659–672, 1999.

[2] D. H. Hughes, S. Serjeant, J. Dunlop, M. Rowan-Robinson, A. Blain, R. G. Mann, R. Ivison, J. Peacock, A. Efstathiou, W. Gear, *et al.*, "High-redshift star formation in the hubble deep field revealed by a submillimetre-wavelength survey," *Nature*, vol. 394, no. 6690, pp. 241–247, 1998.

[3] J. Greaves, W. Holland, G. Moriarty-Schieven, T. Jenness, W. Dent, B. Zuckerman, C. McCarthy, R. Webb, H. Butner, W. K. Gear, *et al.*, "A dust ring around epsilon eridani: Analog to the young solar system," *The Astrophysical Journal Letters*, vol. 506, no. 2, p. L133, 1998.

[4] W. Holland, W. Duncan, and M. Griffin, "Bolometers for submillimeter and millimeter astronomy," in *Single-Dish Radio Astronomy: Techniques and Applications*, vol. 278, pp. 463–491, 2002.

[5] D. Benford, "Langley's bolometer." https://www.researchgate.net/figure/Bolometric-instrument-of-S-P-Langley$_fig1_231110734. Accessed 2021.$

[6] E. S. Agency, "Spire instrument and calibration." https://www.cosmos.esa.int/web/herschel/spire-overview. Accessed 2021.