Far Infrared and Submillimeter Detectors

Xu Huang Apr. 2011

Star Formation in Henize 206

Spitzer Space Telescope • IRAC • MIPS

Visible: R.C. Smith (NOAO)
ssc2004-04a

NASA / JPL-Caltech / V. Gorjian (JPL)
Outline

- Background
- Devices
  - Photoconductors
  - Bolometers
  - Heterodyne Receivers
- Case study-Herschel
25-450 microns

Visible light observable from Earth, with some atmospheric distortion.

Most of the infrared spectrum absorbed by atmospheric gasses (best observed from space).

Radio waves observable from Earth.

Long-wavelet radio waves blocked.

http://en.wikipedia.org/wiki/Optical_window
A Short History

- 1878 Langley- bolometer theory
- After 1959, modern bolometers-carbon resistor
- 1970 The first molecular line CO 115GHz
  GaAs Schottky-barrier diode mixer
- 1970\textsuperscript{th} superconductor bolometers
- 1979 first SIS Mixer
- 1992 first Nb SIS Mixer, 492GHz
Devices

- Photoconductors
- Bolometer

The distinguishing characteristic is that in a thermal detector the excitations generated by the photons relax to a thermal distribution at an elevated temperature (in the thermometer) before they are detected.

- In the photon detector, the nonthermal distribution of excited electrons (e.g., in the conduction band) is detected before it relaxes (e.g., to the conduction band).

- Heterodyne Receiver
Photoconductors

Ge:Ga

Figure 2. Spectral Response for Stressed and Unstressed Ge:Ga.

Figure 5. MIPS Flight 70 µm Array

E. T. Young, 2000
Table 1. Typical Parameters for Unstressed Ge:Ga Photoconductors

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceptor Concentration</td>
<td>$2 \times 10^{14}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Donor Concentration</td>
<td>$&lt;1 \times 10^{11}$ cm$^{-3}$</td>
</tr>
<tr>
<td>Typical Bias Field</td>
<td>50 mV/mm</td>
</tr>
<tr>
<td>Responsivity</td>
<td>7 A/W</td>
</tr>
<tr>
<td>Quantum Efficiency</td>
<td>20%</td>
</tr>
<tr>
<td>Dark Current</td>
<td>$&lt;200$ e$^{-}$/s</td>
</tr>
<tr>
<td>Operating Temperature</td>
<td>1.8 K</td>
</tr>
</tbody>
</table>

E. T. Young, 2000
Bolometers

- Basic Operation
- Responsivity
- Noise
- Examples
- Superconductor TES Bolometers
Basic Operation

\[ P_{in} = P_0 + \eta P_v(t) = GT_1 + C \frac{dT_1}{dt} \]

- Thermal link
- Heat capacity \( C \)
- Thermal conductance \( G \)
- Quantum efficiency \( \eta \)
- Thermal time constant \( \tau_T = \frac{C}{G} \)
Responsivity (Voltage)

\[ P_1 = I^2 R(T) \]  
Electrical power dissipated in the detector

\[ P_{\text{in}} = P_0 + \eta P_v(t) = GT_1 - \frac{dP_1}{dT} T_1 + C \frac{dT_1}{dt} \]

\[ \alpha(T) = \frac{dP_1}{P_1 dT} = \frac{1}{R} \frac{dR}{dT} < 0 \]  
\( \alpha(T) \) temperature coefficient of resistance

Responsivity \[ S_A = \frac{dV}{dP} = \alpha(T) V \left( \frac{dT}{dP} \right) = \alpha(T) V / (G - \alpha(T) P_1) \]
Does not depend on wavelength

Electrical time constant \[ \tau_E = \frac{C}{G - \alpha(T) P_1} \]
Source of Noise

Noise Equivalent Power (NEP) (W Hz\(^{-1/2}\))

\[
\frac{S}{N} = \frac{P_s}{\text{NEP}(df)^{1/2}}
\]

- a) Johnson noise – randomly fluctuating potential energy on the capacitor
- b) Thermal noise – fluctuations of entropy across the thermal link
- c) Photon noise – Poisson statistics of the incoming photon stream

\[
\begin{align*}
\text{NEP}_j &\approx \begin{cases} 
GT^2 \text{ (if } \alpha(T) \approx T^{-3/2}) \\
GT^{3/2} \text{ (if } \alpha(T) \approx T^{-1}) 
\end{cases} \\
\text{NEP}_r & = \frac{(4kT^2G)^{1/2}}{\eta} \\
\text{NEP}_{ph} & = \frac{hc}{\lambda} \left( \frac{2\varphi}{\eta} \right)^{1/2}
\end{align*}
\]

\[
\text{NEP} = (\text{NEP}_j^2 + \text{NEP}_r^2 + \text{NEP}_{ph}^2 + ...)^{1/2}
\]
Superconducting Bolometers

- TES (Transition Edge Sensor) bolometers
- SQUID (Superconducting Quantum Interface Device) amplifiers

\[
P_1 = \frac{V^2}{R}
\]
Heterodyne Receivers

- a) High quality, fast photon detectors are not available at wavelengths longer than the infrared.

- b) Efficient absorption of the energy of the photons by a device require the device to have dimensions at least comparable to the photon wavelength.

- c) Coherent receiver- measure and preserve phase information directly, easily adapted for spectroscopy, make interferometry between different receivers possible.
\[ I \propto V^2 \propto P = (E_{\text{sig}} \cos(\omega_{\text{sig}} t + \varphi) + E_{\text{LO}} \cos(\omega_{\text{LO}} t))^2 \]

\[
= \frac{E_{\text{sig}}^2 + E_{\text{LO}}^2}{2} + \frac{E_{\text{sig}}^2}{2} \cos(2\omega_{\text{sig}} t + 2\varphi) + \frac{E_{\text{LO}}^2}{2} \cos(2\omega_{\text{LO}} t) + E_{\text{sig}} E_{\text{LO}} \cos((\omega_{\text{sig}} + \omega_{\text{LO}}) t + \varphi) \\
+ E_{\text{sig}} E_{\text{LO}} \cos((\omega_{\text{sig}} - \omega_{\text{LO}}) t + \varphi)
\]

Constant component: \( \frac{E_{\text{sig}}^2 + E_{\text{LO}}^2}{2} \)

High frequency component: \( \frac{E_{\text{sig}}^2}{2} \cos(2\omega_{\text{sig}} t + 2\varphi) + \frac{E_{\text{LO}}^2}{2} \cos(2\omega_{\text{LO}} t) + E_{\text{sig}} E_{\text{LO}} \cos((\omega_{\text{sig}} + \omega_{\text{LO}}) t + \varphi) \)

Beat component: \( E_{\text{sig}} E_{\text{LO}} \cos((\omega_{\text{sig}} - \omega_{\text{LO}}) t + \varphi) \)

IF signal: \( E_{\text{sig}} E_{\text{LO}} \cos((\omega_{\text{sig}} - \omega_{\text{LO}}) t + \varphi) \)

Time response \( \sim 1/f_{IF} \) nanoseconds

http://en.wikipedia.org/wiki/Heterodyne_detection
SIS Mixers

Superconductor-Insulator-Superconductor

Photon-assisted tunneling of single electron quasiparticles

\[ eV_0 > \Delta_1 + \Delta_2 - n\hbar\omega \]

Up frequency limit- Josephson tunneling

\[ f_u = \frac{2\Delta}{\hbar} \]

Magnetic field to suppress tunneling current, \(2f_u\)

\(\text{Nb } 12\times10^{11}\text{Hz}\)

J. R. Tucker & M. J. Feldman, 1985
Noise Temperature

Quantum limit \( T_N \approx \frac{hv}{k} \)

Thermal limit \( T_N \approx T_B \)

Mixer noise temperature \( T_M = \frac{e}{4k} \frac{1}{\Psi} \)

Figure of merit \( \Psi = \frac{d^2I/dV^2}{2dI/dV} \)

A matched blackbody at the receiver input at a temperature \( T_N \) produces: S/N=1

Detection of Light, G.H. Rieke.
Performance Comparison

- a) Bolometer at background limit & Heterodyne receiver in the thermal limit ($h\nu << kT_B$)

$$\frac{(S / N)_{coh}}{(S / N)_{inc}} = \left[ \frac{1}{\eta} \frac{\Delta f_{IF}}{\Delta \nu} \right]^{1/2} \frac{hv}{kT_B}$$

- b) Bolometer at detector noise limit & Heterodyne receiver at quantum limit

$$\frac{(S / N)_{coh}}{(S / N)_{inc}} = \frac{NEP(\Delta f_{IF})^{1/2}}{2h\nu \Delta \nu}$$

- c) Bolometer at background noise limit & Heterodyne receiver at quantum limit

$$\frac{(S / N)_{coh}}{(S / N)_{inc}} \approx \frac{2.6 \times 10^{11} Hz}{\nu}$$

Detection of Light, G.H. Rieke.
Herschel

**PACS**: (60-85, 85-130, 130-210 µm)
Bolometer Array for photometry
Ge:Ga photoconductor array for spectroscopy

**SPIRE**: (above 200 µm)
“Spider-web” bolometer arrays for long wavelength
Camera and low to medium resolution spectrometer

**HIFI**:
SIS mixer (480-1250GHz)
HEB mixer(1410-1910GHz)
Very high resolution heterodyne spectrometer

http://en.wikipedia.org/wiki/Herschel_Space_Observatory
Conclusion

- Exciting new area, fast developing
- **Detector of choice:**
  - Photoconductors ($\lambda < 160$ micron)
  - Bolometers (continuum detection)
  - Heterodyne mixers (high resolution spectrum)
- **Expectation:** new superconducting material with better performance
Reference


- Detection of Light: From the Ultraviolet to the Submillimeter/ G.H. Rieke. – 2nd ed. University of Arizona.