Detection of Light

Heterodyne Receivers

(part III)

10 Dec 2009

See http://www.strw.leidenuniv.nl/~brandl/DOL/Detection_of_Light.html for more info

Reminder: Noise & Antenna Temperatures

Noise Temperature

Previously, we have sseen that $NEP_H \propto \sqrt{2\Delta f_{IF}}$, which implies that the the S/N increases when narrowing down the bandwidth. This is only correct if all power falls within a narrow interval, which is smaller than Δf_{IF} (o.k. for emission lines but *not* for continuum sources).

To describe the performance of heterodyne detectors we introduce the noise temperature T_N.

The noise temperature T_N is *defined such that a matched blackbody at the receiver input at a temperature T_N produces a S/N = 1.*

Obviously, the lower T_N the better the S/N.

Antenna Temperature

Just like the noise temperature describes the strength of the *noise background* (S/N=1) we can assign the <u>*source flux*</u> an antenna temperature T_S.

In the Rayleigh-Jeans approximation ($h\nu \ll kT$) we can write:

$$P_S = L_\nu(T_S) A\Omega\Delta f_{IF} \overset{\substack{Rayleigh \\ JeansBB}}{=} \frac{2kT_S\nu^2}{c^2} A\Omega\Delta f_{IF} \overset{A\Omega=\lambda^2=\frac{c^2}{\nu^2}}{=} 2\Delta f_{IF} kT_S$$

where $2\Delta f_{IF}$ is the frequency bandpass for a double sideband receiver.

Hence, in the R-J case, the antenna temperature is linearly related

to the input flux density: $P_S \sim T_S$

How to measure the Noise Temperature

Consider two blackbody emitters, one at T_{hot} and one at T_{cold}.

If V is the output voltage of the receiver we can define a "Y-factor":

$$Y = \frac{V_{hot}}{V_{cold}}$$

which can be measured by alternately placing the blackbodies over the receiver input.

Since $V \sim T_{loads} + T_{receiver}$ we get: $Y = \dfrac{T_{hot} + T_{rec}}{T_{cold} + T_{rec}}$

and solve it for the receiver noise temperature:

$$T_{rec} = \frac{T_{hot} - YT_{cold}}{Y - 1}$$

Performance Comparison: Coherent and Incoherent Receivers

Performance Ratio of In/Coherent Receivers

The achievable S/N for a *coherent* receiver in terms of antenna and system noise temperatures is given by the Dicke radiometer equation:

$$\boxed{\left(\frac{S}{N}\right)_{coh} \approx \frac{T_S}{T_N^{sys}}\left(\Delta f_{IF}\Delta t\right)^{1/2}}$$

From the definition of the NEP $(S/N) = \frac{P_S\sqrt{2\Delta t_{\text{int}}}}{NEP}$ and $\frac{P_S}{\Delta\nu} = 2kT_S$

we get for the S/N of an incoherent receiver (operating at the diffraction limit):

$$\boxed{\left(\frac{S}{N}\right)_{inc} = \frac{2kT_S\Delta\nu_{inc}\left(\Delta t\right)^{1/2}}{NEP_{inc}}}$$

Hence, the performance ratio between these two types of receivers is:

$$\frac{(S/N)_{coh}}{(S/N)_{incoh}} = \frac{NEP_{inc}\left(\Delta f_{IF}\right)^{1/2}}{2kT_N^{sys}\Delta\nu_{inc}}$$

, where $\Delta\nu$ and NEP refer to the incoherent detector, and Δf_{IF} and T_N^{sys} refer to the coherent receiver.

Example 1: BLIP and thermal Limit

Consider a bolometer operating at the background limit (BLIP) and a heterodyne receiver operating in the thermal limit ($h\nu \ll kT$).

Both receivers view the source through an etendue $A\Omega = \lambda^2$ and a background of unity emissivity at T_B. Then:

$$\frac{(S/N)_{coh}}{(S/N)_{incoh}} = \frac{NEP_{inc}\left(\Delta f_{IF}\right)^{1/2}}{2kT_N^{sys}\Delta\nu_{inc}} = \ldots = \left[\left(\frac{1}{\eta}\right)\left(\frac{\Delta f_{IF}}{\Delta\nu_{inc}}\right)\left(\frac{h\nu}{kT_B}\right)\right]^{1/2}$$

In other words, in this case the bolometer will perform better – unless $\Delta f_{IF} \gg \eta\Delta\nu$!

The latter case will be given for measurements at high spectral resolution, much higher than the IF bandwidth.

Example 2: Quantum Limit

Consider a detector noise-limited bolometer and a heterodyne receiver operating at the quantum limit (hν»kT). Then:

$$\frac{(S/N)_{coh}}{(S/N)_{incoh}} = \frac{NEP_{inc}(\Delta f_{IF})^{1/2}}{2kT_N^{sys}\Delta\nu_{inc}} = \ldots = \frac{NEP_{inc}(\Delta f_{IF})^{1/2}}{2h\nu\Delta\nu_{inc}}$$

In the case of narrow bandwidth and high spectral resolution, the heterodyne receiver will outperform the bolometer.

If the spectral resolution $\nu/\Delta\nu$ is kept constant over the observed range the figure of merit goes as $1/\nu^2$.

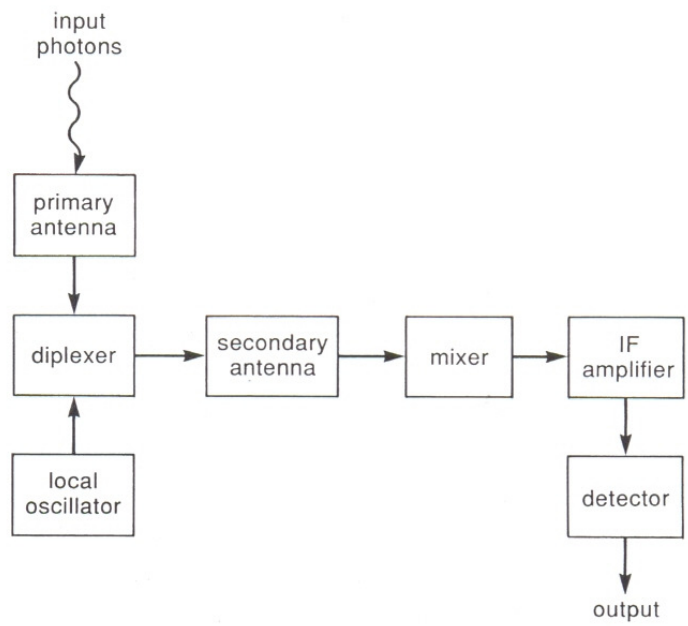
An additional gain may come from the spectral multiplexing (filter banks etc.)

Differences between IR and sub-mm Receivers

Heterodyne Receivers: IR ⇔ (sub-)mm

Commonalities:

- approach: mixing signal with reference wave → down-converting frequency
- conceptual path: → mixer → IF amplifier → detector → output
- limited bandpass → high resolution spectroscopy
- diffraction-limited throughput



Differences:

1. mixer technology
2. local oscillator technology

Differences in LO Technology

The LO power can be fed to the mixer via a second waveguide or reflecting from a diplexer.

At high frequencies the LO may be a continuous wave (CW) laser

+ high power

- discrete set of frequencies

At lower frequencies one may use an electronic LO → wire antenna or waveguide.

+ easily tuneable in frequency

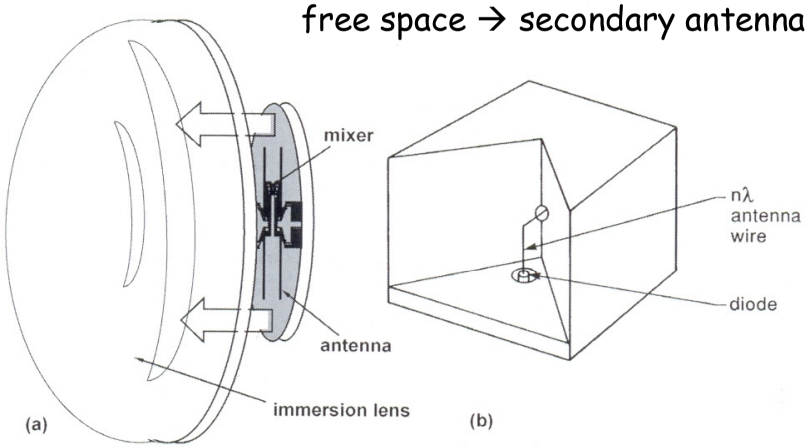
- low power at high frequencies (sub-mm)

Most of the previously discussed performance limits apply equally to optical/IR and sub-mm/millimeter heterodyne receivers.

The Secondary Antenna

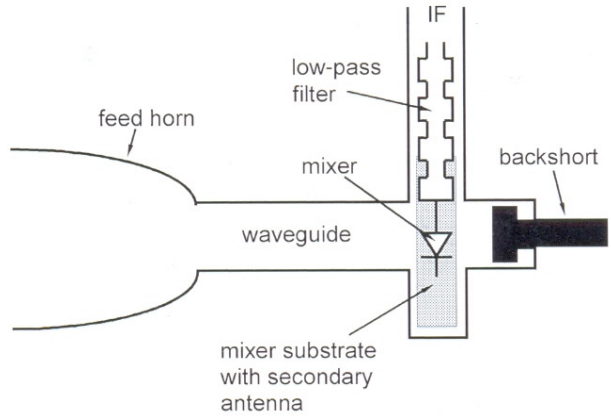
The secondary antenna is a wire or lithographic structure.

Challenge: efficient transfer of power from
free space → secondary antenna → mixer



←← often a lens is used to concentrate the power onto a planar antenna.

← corner reflector (mixer at the bottom hole)



At frequencies below 1000 GHz (300μm):
→ feed horn → waveguide

(Quite efficient, but not suitable for shorter wavelengths due to manufacturing tolerances.)

Differences in Mixer Technology

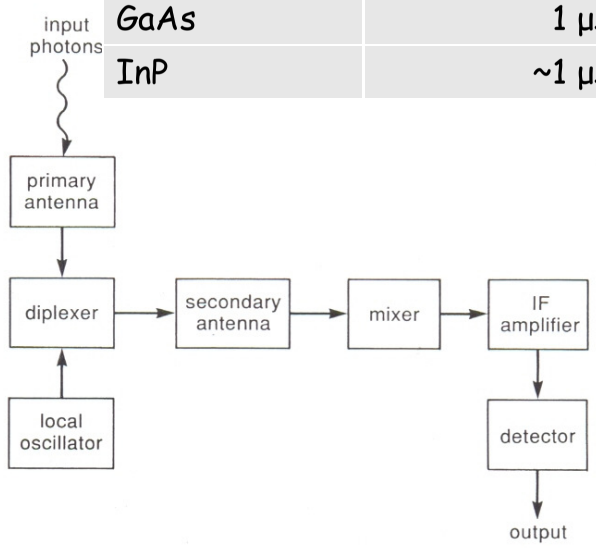
1. Good & fast photon detectors for the sub-mm do not exist for $\lambda > 40\mu m$.
2. "pixel" size ~ λ (for efficient absorption). But frequency response $\propto$ 1/size

➔ optimized *electrical* components

Material	Recombination time
Si	100 μs
Ge	10000 μs ←
PbS	20 μs
InSb	0.1 μs
GaAs	1 μs
InP	~1 μs

Generally, photo-diode mixers have a frequency response limited to < 1GHz by the recombination time required for charge carriers that have crossed the junction

➔ Schottky diode, SIS or HEB mixers.



Important Components of sub-mm Receivers

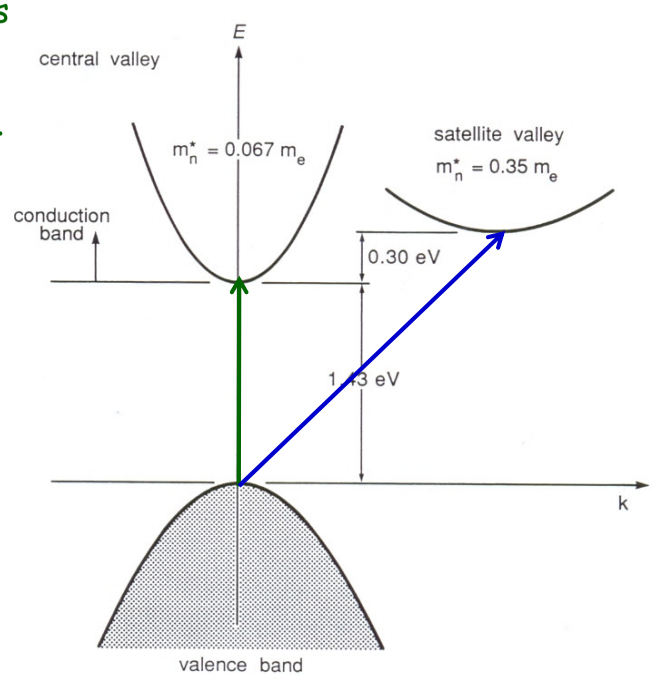
I. Gunn Oscillators [LO]

Gunn Oscillators

Based on GaAs or InP devices (here: n-type GaAs)

1. full valence band and electric field is small (< 3000 V/cm): conduction electrons will be excited at **k** = 0 (just like for other semiconductors).

2. If electric field is high (> 3000 V/cm): electrons gain sufficient energy to be scattered into the satellite valley.



In the satellite band the ...

- effective density of states is ~70× higher → long lifetimes.

- electron mobility μ is much lower → current decreases ($I_x = qn\mu_e E_x$)

→ If electric field exceeds a critical value then dJ/dE < 0

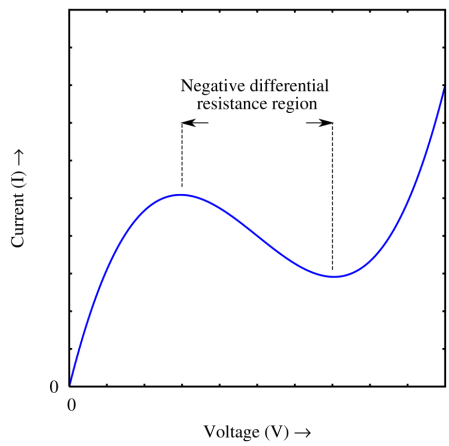
Side Note: Negative Resistance

(from Wikipedia:)

Negative resistance is a property of some electric circuits where an increase in the current entering a port results in a decreased voltage across the same port.

This is in contrast to a simple ohmic resistor, which exhibits an increase in voltage under the same conditions.

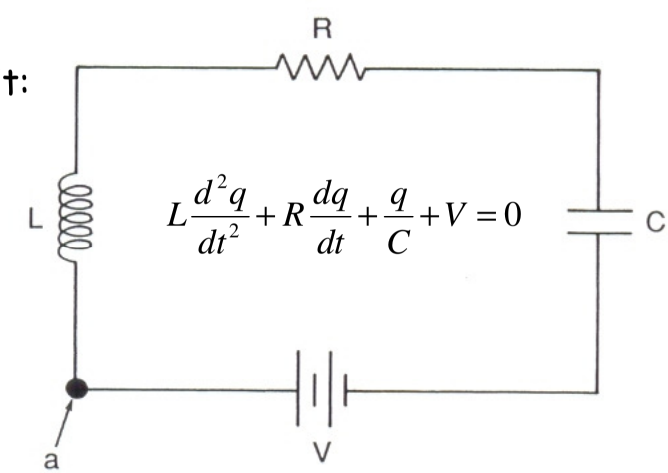
Negative resistors are theoretical devices; however, some types of diodes can be built that exhibit negative resistance in some part of their operating range.



Gunn Oscillators (2)

Gunn oscillators can be operated in limited charge accumulation mode: the voltage across the device is varied rapidly and it maintains a negative resistance.

Consider a simple oscillator circuit:



$$L\frac{d^2q}{dt^2}+R\frac{dq}{dt}+\frac{q}{C}+V=0$$

If R < 0 an oscillatory voltage builds up in the circuit until its amplitude is limited by dissipation in elements with positive resistance. The voltage will oscillate with frequency:

$$\omega=\left[\frac{1}{LC}-\left(\frac{R}{2L}\right)^2\right]^{1/2}$$

Gunn oscillators are good LOs from 30 – 150 GHz up to ~100 mW.
For ν < 100 GHz material is GaAs; for ν > 100 GHz one prefers InP.

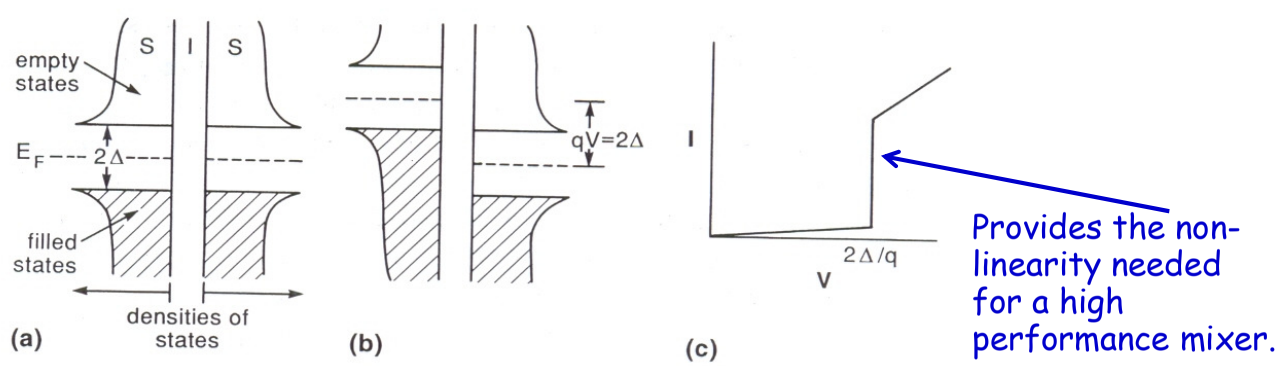
Important Components of sub-mm Receivers

II. SIS Junctions [Mixer]

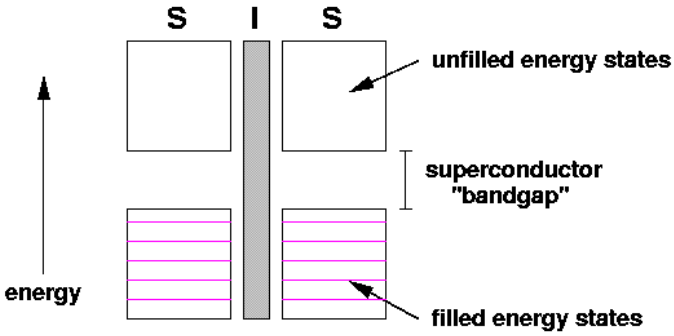
SIS Junctions

Reminder: two superconductors separated by an insulator thinner than the binding distance of a Cooper pair
→ superconductor – insulator – superconductor (SIS) (Nb – Al_2O_3 – Nb)

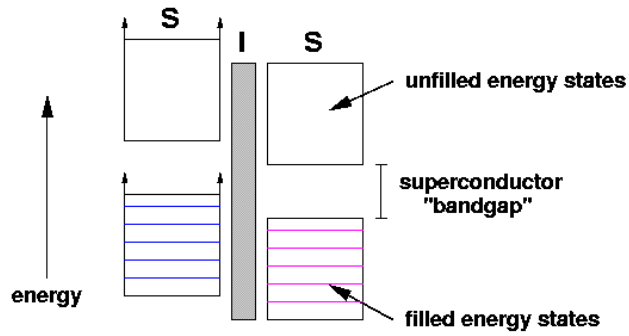
1. No voltage: Cooper pairs can flow from one superconductor to the other and carry small currents (Josephson effect)
2. Small voltage applied: shifts energy states, but insulator blocks "normal" currents.
3. Larger voltage applied: if the voltage just exceeds the energy gap → significant current via "quasiparticle tunneling through the insulator".



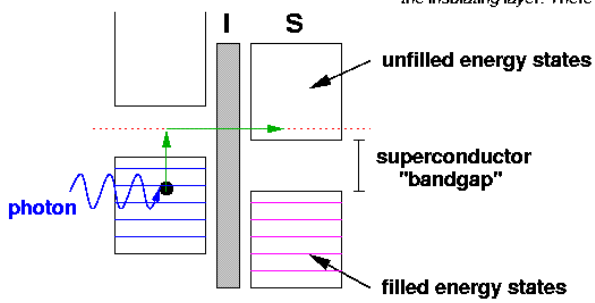
$$I_{tunnel} \sim n_{filled\ states\ (left)} \times n_{empty\ states\ (right)} \times P_{tunneling}$$



An unbiased SIS junction allows superconducting electron pairs to travel unimpeded across the insulating layer. Energy states are identical for both superconducting layers.



Biasing a SIS junction shifts the energy levels of one superconductor with respect to the other. Since energy levels are no longer coincident across the junction, superconducting pairs of electrons are "blocked" by the insulating layer. There is no current flow across the junction.



The optimal biasing level will allow a submillimeter photon of the desired frequency or energy to boost the superconducting electron to the other side of the insulative potential barrier by filling in an empty energy level in the other superconducting layer. This yields a large current flow for a photon "impact"; the desired effect.

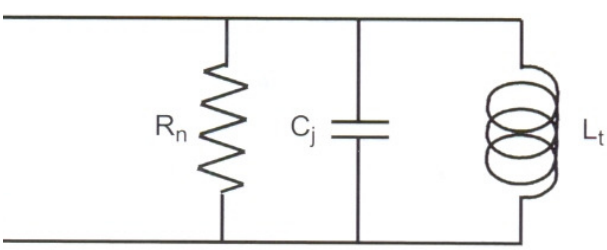
Taken from SORAL website (U of Arizona): http://soral.as.arizona.edu/overview.html

SIS Junctions (2)

General problem: high capacitance of the SIS junction (typically 10× higher than for Schottky diodes)

Solution: mount SIS junction in an arrangement that uses inductances to cancel out most of its capacitance. The tuning inductance is provided by a superconducting stripline.

Maximum power when impedances of capacitor and inductor cancel.

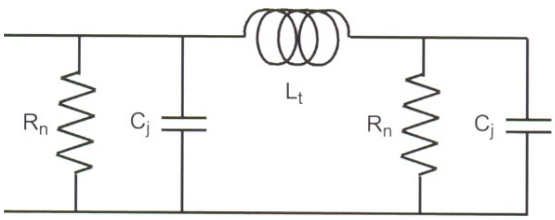


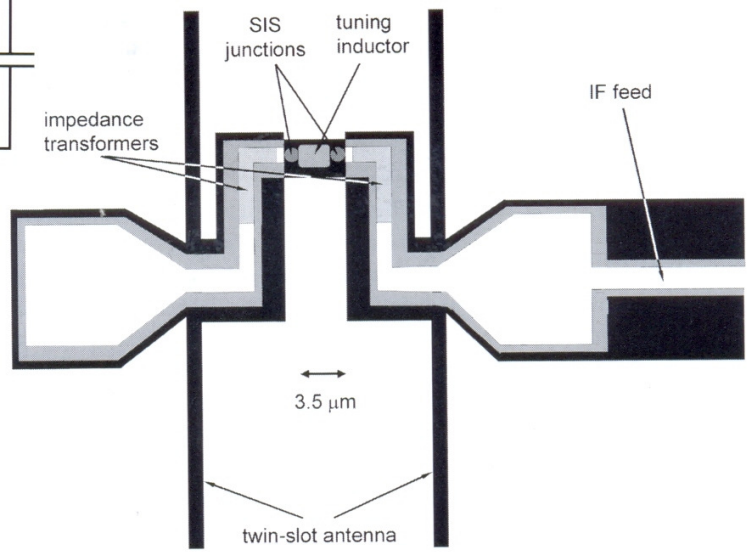
Schematics:
R_n = normal mixer resistance
C_j = junction capacitance
L_t = stripline tuning inductance

SIS Junctions (3)

Problem: additional elements are required: termination with an RC short-circuit.

Solution: use two identical (dual) junctions (for impedance matching), separated by the microstrip tuning inductance.





Important Components of sub-mm Receivers

III. Hot Electron Bolometer [Mixer]

Hot Electron Bolometers (1)

Bolometers for sub-mm/mm wavelengths can make use of n-type InSb:

• Impurity levels ~ conduction band → 0.001 eV sufficient to create free electrons → see of free electrons.

• Incident photons are absorbed by the free electrons → absorption raises their energies above thermal equilibrium: hot electrons

• De-excitation (lattice interaction is weak) → long lifetimes, high densities

• Hot electrons significantly affect the mobility (and thus the conductivity) ➔ measuring the resistance means monitoring the photon signal.

Example: thermal conductance $G = 5\times10^{-5}$ W/K
typical $n \sim 5\times10^{13}$ cm^{-3}
typical $\tau \sim 2\times10^{-7}$ s fast!
typical NEP $\sim 2\times10^{-13}$ W (Hz)$^{-1/2}$ low!

Hot Electron Bolometers (2)

Generally:
• bolometer elements must be small
• feed arrangements similar to SIS and Schottky → same single mode restrictions

SIS junctions, Schottky diodes and HEBs all become less effective as mixers at frequencies above 10^{12} Hz.

QE depends on absorption efficiency of the free electrons.
At long λ the absorption is λ-independent and high, but at short λ the absorption goes as λ^2;
→HEBs are inefficient at wavelengths shorter than ~300 μm

The speed of the classical HEB is limited by relaxation time $\tau \sim 10^{-7}$ s
→ Δf_{IF} < few MHz

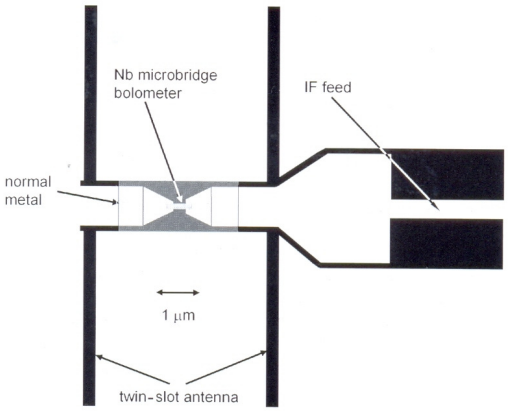
Superconducting Hot Electron Bolometers

Electrons in a superconductor do not lose energy easily to the metal lattice.

Make very small devices (size << wavelength). Energy is coupled into the bolometer electrons with an antenna structure.
→ microbolometer → very short response times.

Superconducting thin film HEBs extend the range to higher frequencies than the other mixer types. They are the choice of heterodyne detector for the frequencies between 1.5 and 6 THz.

HEB mixer: energy is coupled from the antenna into a sub-micron strip of superconducting Nb or NbTiN extending between two pads of normal metal.



Hot Electron Nano-Bolometer

Material: Titanium and Niobium metals

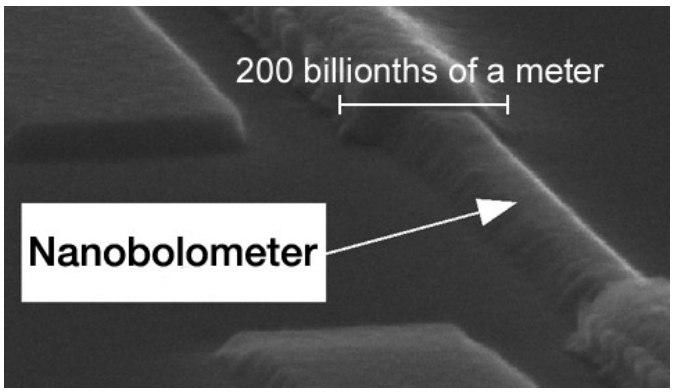
Size: about 500 nanometers long and 100 nanometers wide

Construction via thin-film and nanolithography techniques

Operating temperature: 0.1 K

Sensitivity: ~100 x bette than exisitng bolometersr

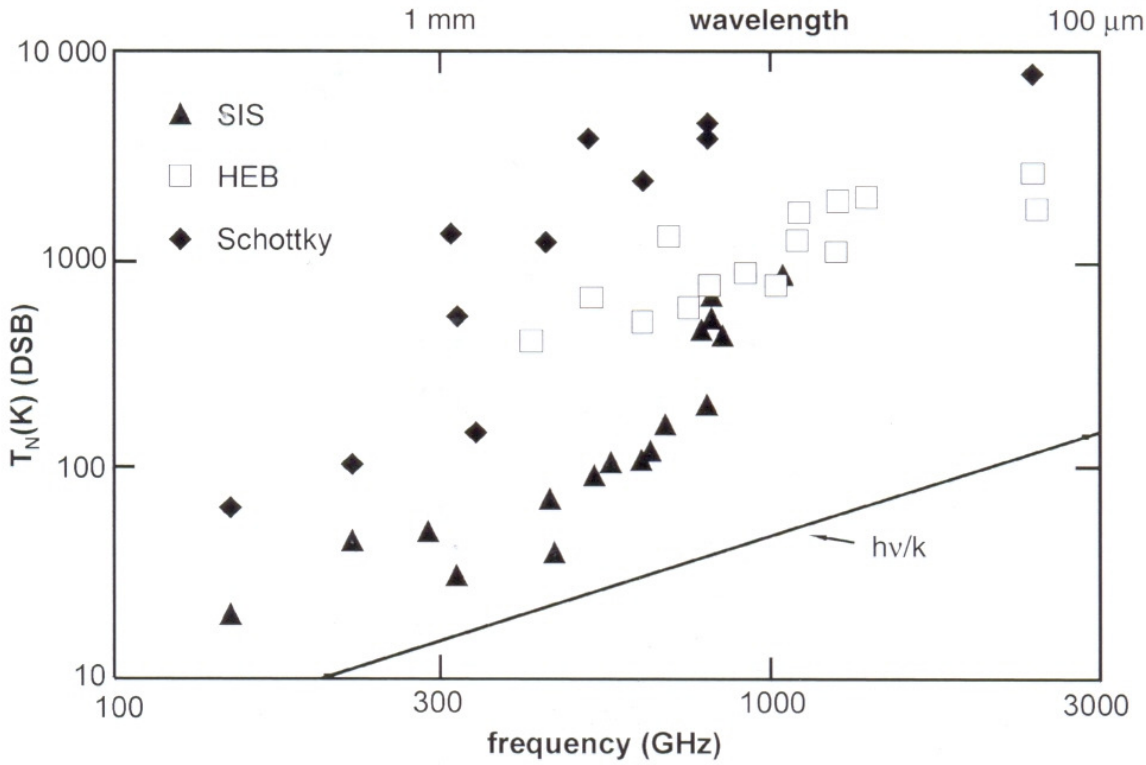
Photons heat electrons in the titanium section, which is thermally isolated from the environment by superconducting niobium leads. The device can detect as little as a single photon of far infrared light.



http://www.jpl.nasa.gov/news/phoenix/release.php?ArticleID=1783

Noise Temperatures for different Mixer Types

Achieved performances of high frequency heterodyne receivers.
The quantum limit is shown as solid line.



Outlook: MKIDS

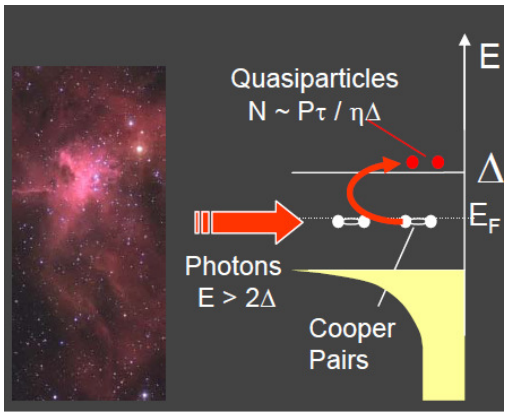
MKIDS

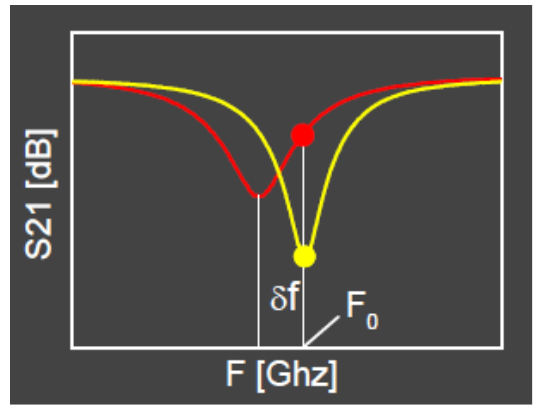
A new kind of detector

MKID = Microwave Kinetic Inductance Detector

Principle: Photons are absorbed in a superconductor, producing quasi-particle excitations, which change the surface reactance (= kinetic inductance) of the superconductor → monitor changes in KI.

Based on thin film superconducting microwave resonator , whose resonance frequency shifts when Cooper pairs are broken apart by the absorption of a photon.





Comparison

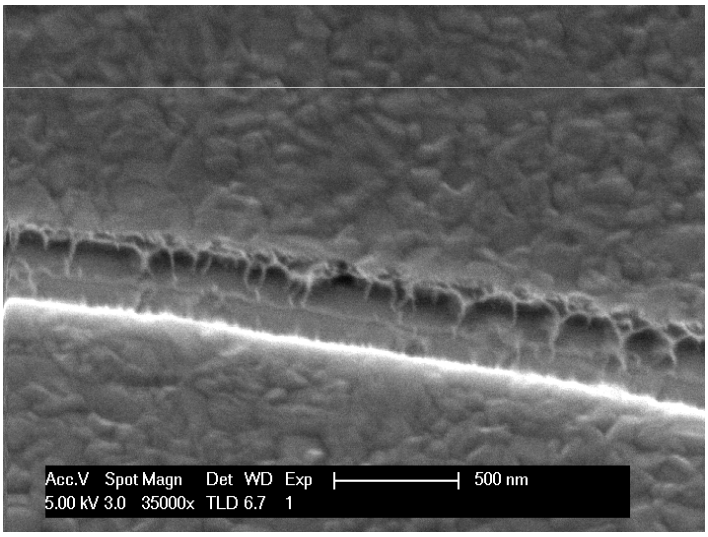
Property	BIB In:As (MIRI)	Ge:Ga (AKARI)	TES (SCUBAII)	KIDS
NEP ($WHz^{-0.5}$)	10^{-18}	10^{-18}	$2.5*10^{-17}$ $1.9*10^{-19}$	$7*10^{-19}$
Quantum Efficiency (%)	>70	20	40-80	35
#Pixels per chip	10^6	1024	1280	10^4
Minimum pixel size (μm)	18	500	~1000	500
Positive Points	Mature	Mature	Proven Technology	Easy multiplexing Simple production
Negative Points	λ < 20 (μm) Cryogenics	Cryogenics	Complex Multiplexing	Antenna limited

Improving MKIDs (An SRON/TUD Project)

$$NEP^2(\omega) = (S_\vartheta(\omega))^2 \left(\frac{\eta\tau}{\Delta} \frac{\delta\vartheta}{\delta N_{qp}} \right)^{-2} \propto \frac{Q^2}{t} \frac{t^2 * t^{0.88}}{Q^2} \propto t^{1.88}$$

Due to diffusive scattering:
- QP diffusion length limited by min(t,s)
- Low diffusion length → high QP concentration
- Reduction QP lifetime (τ)

➔Reduce thickness *t* (size)



First cleanroom results:

- Film: 100 nm sputter deposited aluminum
- E-beam Lithography
- Wet etching
  not below 500 (nm)

Gao, PhD 2008
Porch et al, IEEE 2005

The End