A BROADBAND LOW NOISE SIS RECEIVER FOR SUBMILLIMETER ASTRONOMY

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ABSTRACT

A quasioptical heterodyne receiver using a Pb alloy superconductor-insulator-superconductor (SIS) tunnel junction as the detector and a planar logarithmic spiral antenna for the RF coupling is described. Noise measurements were made at frequencies between 115 GHz and 761 GHz, yielding noise temperatures (DSB) ranging from 33 K to 1100 K.

INTRODUCTION

Among the heterodyne receivers with a large instantaneous bandwidth, those using superconductor-insulator-superconductor (SIS) tunneling junctions as the detector are the most sensitive for millimeter wave radiation (1,2,3). The common design for millimeter wave heterodyne receivers used in radio astronomy utilizes waveguide structures to couple the radiation to the detector. Waveguide structures typically yield a tuning range of about 30% (4). Using more than one tuning element, the range can be pushed to one octave (2,5). These tuning elements are undesirable because they complicate the operation of the receiver and can suffer from irreproducible back lash and mechanical wear.

An alternative to the waveguide structure is to mount the detector at the center of a planar microantenna which provides quasioptical coupling between the telescope and the detector. This avoids the problems of tuners and high frequency waveguide component fabrication and offers the potential of high-performance operation over many octaves with a single receiver. Wengler *et al.* (6) built a quasioptical receiver using a bow-tie antenna mounted on a hyperhemispherical lens (7) to couple radiation to the SIS junction. It was the first heterodyne receiver with a large instantaneous bandwidth and covered a frequency range of 2 octaves (116 to 466 GHz). Bow-tie antennas have a frequency independent impedance (8) and symmetric E- and H-plane response, as long as their linear dimensions are larger than a free space wavelength. However, in theory their beam patterns do not show a single main beam perpendicular to the antenna-plane, which is the desired direction of radiation, but instead show a complex large angle pattern (8). In practice (6) the beam can be pulled forward by a lens system. Wengler *et al.* observed noise temperatures almost as good as those for narrow band SIS waveguide receivers, which was very encouraging.

We have built a new receiver based on the same principles, using a planar two-arm logarithmic spiral antenna (Figure 1), rather than a bow-tie. In addition to frequency independent impedance and symmetric E- and H-planes these antennas have frequency independent beam patterns with a main beam perpendicular to the antenna-plane (9). Side lobes are about 15 dB lower relative to the main beam. This receiver is essentially as sensitive as the best SIS waveguide receivers in the millimeter band and shows superior performance in the submillimeter band. Its design frequency range is 100 to 1000 GHz and noise temperature measurements between 115 and 761.4 GHz were made. In addition to laboratory measurements, this receiver has been tested at 115, 230 and 345 GHz at the Caltech Submillimeter Observatory (CSO) on Mauna Kea, Hawaii. As far as we know, this is the first SIS quasioptical receiver to have been successfully operated for submillimeter wave astronomy.

RECEIVER DESCRIPTION

The overall layout of the receiver is shown in Figure 2. The SIS detector, spiral antenna, RF optics and IF chain are described in more detail below.

a) SIS Detector
The PbInAu SIS tunnel junctions used for our receiver are produced by us at AT&T Bell Labs. Standard electron beam lithography for the masks and the tri-level photoresist stencil technique (10,11) were used for the fabrication of the devices (12). A gap voltage of 2.40 mV and a critical current density of 3000 A/cm^2 at a junction temperature of 4.2 K were measured with the SIS junction mounted in the receiver. The junction overlap area is about 0.5 to 1 μm^2 which yields a capacity of about 10 fF. With a normal state resistance of 50Ω the roll-off frequency is about 300 GHz. The two electrodes from the SIS junction extend out to the two arms of the spiral antenna. Hence the antenna and the SIS junction in its center are manufactured simultaneously from the same material (PbInAu) on a single crystal quartz substrate, 4 mm square by .1 mm thick.

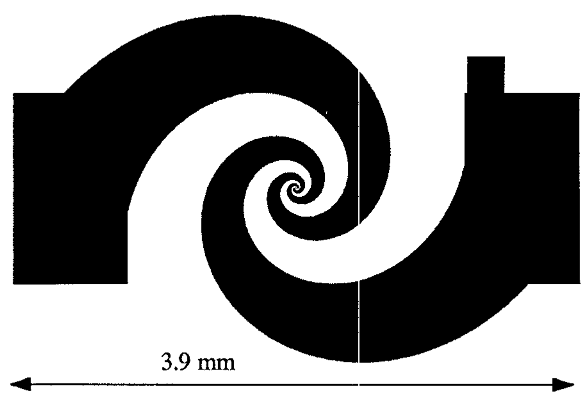

Figure 1 – The planar two-arm logarithmic spiral antenna with the IF ports (contact pads to the left and right).

1 SIS junction
2 Hyperhemisphere
3 Anti reflection coating
4 IR filters and plastic lens
5 Mylar window
6 Conductive plane with Fe core
7 Coil for magnetic field
8 Translation stage
9 SIS junction DC-bias
10 Mixer IF output
11 IF preamplifier
12 IF output
13 Electronics connector
14 Conductive backplane drive
15 Beam splitter

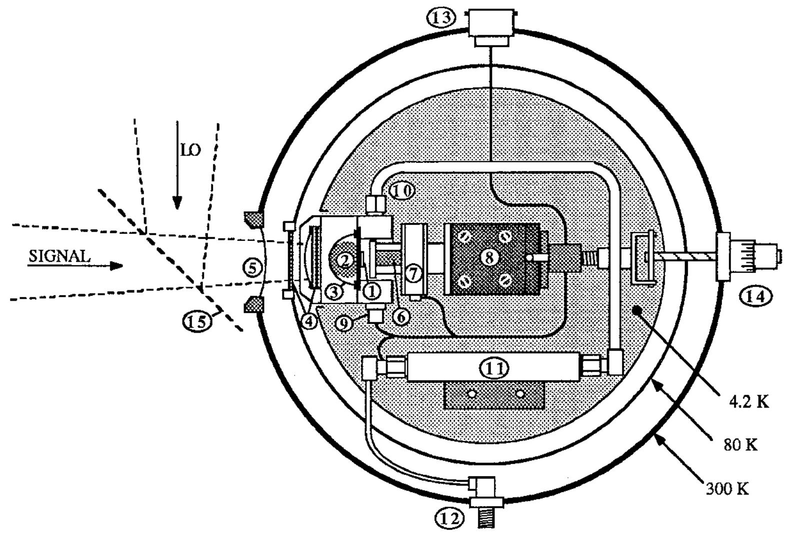

Figure 2 - Receiver layout.

b) Spiral antenna

The planar two-arm logarithmic spiral antenna† (Figure 2) belongs to a family of frequency independent antennas, *i.e.* their characteristics like impedance, beam pattern *etc.* do not depend on frequency over several octaves. Rumsey (13) proposed that this can be achieved when the antenna shape is described without a characteristic length scale but only by ratios (logperiodic antennas) or angles (spiral antennas). The shape for a single arm of a planar spiral antenna is given by

$$r = r_o e^{c\theta}$$

with (r, θ) polar coordinates and c a dimensionless constant (r_o = "one length unit"). Scaling this with wavelength

$$\frac{r}{\lambda} = \frac{r_o e^{c\theta}}{\lambda} = e^{c(\theta - \theta_\lambda)}$$

shows that changing the wavelength results in a rotation of the antenna due to a change of θ_λ. However, since the spiral antenna has circular polarization this is of no concern. In order to have a frequency independent beam pattern the effective aperture must increase with wavelength. This has been experimentally verified by Dyson (14), who showed that the fields decay by about 20 dB in the first wavelength along the spiral arm. Therefore the effective aperture scales with wavelength. Since the fields decay rapidly, the spiral can be truncated at a radius R without affecting the antenna characteristics for $\lambda \leq R$. We chose R = 1.5 mm, yielding an upper wavelength limit outside the dielectric of about 3 mm. An area with about 15 μm radius is needed for the SIS junction with its leads connecting to the spiral, yielding a lower wavelength limit outside the dielectric of about 300 μm. This shortest operating wavelength is about 10 times larger than the scale on which the antenna deviates from the ideal spiral shape.

We chose a self-Babinet-complementary antenna structure, because all such structures with two ports have a constant impedance of $Z_o = 60\pi\Omega \simeq 188\Omega$. Mounting such an antenna on to a half space of dielectric (approximated by the hyperhemisphere) yields an antenna impedance of

$$Z_{ant} = \frac{Z_o}{\sqrt{(1+n^2)/2}} \simeq 114\Omega$$

† also called two-arm equiangular spiral antenna

where n = 2.11, the refractive index of single crystal quartz in the submillimeter region (15).

c) RF optics

The SIS device with the planar antenna structure sits on a dielectric (crystal quartz) substrate which is mounted on the flat side of the hyperhemispherical lens made out of the same material. This produces an asymmetric beam pattern with respect to the antenna plane due to the different dielectric media on each side of the antenna. For crystal quartz one gets a beam-coupling ratio of about 7 dB, in favor of the quartz side (7). To further increase this ratio the antenna is backed up by a conductive plane, which can be moved perpendicular to the plane of the antenna according to the receiving frequency. A hyperhemispherical shaped dielectric lens and also a plastic lens were used to match the incoming beam (*e.g.* from a radio telescope) to the spiral antenna. A series of cooled filters (fused quartz and fluorogold scattering filters) were used to reject wavelengths shortward of 300 μm.

d) IF circuit

The submillimeter signal is converted to an intermediate center-frequency (IF) of 1.5 GHz with a bandwidth of 500 MHz. No RF rejection filter at the terminals of the spiral antenna is necessary, since the RF-fields on the antenna decay rapidly. One arm of the spiral antenna is grounded, the other one leads into a low pass filter. This filter uses the leads to the junction as inductors and the mount of the insulated lead as a capacitor. The cut-off has been set using with a network analyzer in such a way as to short all frequencies above the IF band. The IF signal is amplified by a three stage liquid-helium-cooled preamplifier similar to that described by Weinreb (16), with a high-electron mobility transistor (HEMT) in the first stage. An effective noise temperature of 2 K averaged over the entire bandwidth was measured for this preamplifier.

RESULTS

Table 1 shows the receiver's noise performance averaged over a 500 MHz bandwidth. These measurements were made using hot (290 K) and cold (78 K) loads. In order to verify the results at 115, 230 and 345 GHz the receiver was tested at the Caltech Submillimeter Observatory (CSO) on Mauna Kea, Hawaii. A Gunn oscillator and a Schottky diode multiplier (17) were used to supply local oscillator (LO) power at these frequencies. At the higher frequencies measurements were made in the laboratory using a far-infrared laser as the LO power source. The Josephson currents had to be suppressed with a magnetic field for frequencies above 350 GHz (18). A conversion loss for the mixer could not be measured precisely, since the matching between the mixer and the IF amplifier is not well known. However, at 345 GHz the loss is estimated to be about 12 dB.

Table 1.

Frequency [GHz]	115	230	345	525	761
T_{sys} (DSB) [K]	33	116	215	470	1100

Figure 3 shows a comparison of the spiral antenna receiver with the bow-tie antenna receiver and state of the art Schottky and SIS waveguide receivers. Figure 4 shows a typical beam pattern taken at λ = 1 mm. The sidelobes are probably due to diffraction of the beam the dewar windows, since scale-model measurements of the antenna alone do not show them (19). However, they are about 15 dB below the main beam which is sufficient for most radio astronomy applications. During the first set of astronomical measurements the main beam efficiency at 345 GHz was about 30 %, which is lower by a factor of 2 than expected. This was attributed to a focusing problem inside the mixer block, which has now been rectified. Figure 5 shows a spectrum of a molecular cloud in the Orion region (OMC1) at 341.54 GHz LO frequency. This spectrum was integrated for 3.5 hours down to the confusion limit, *i.e.* where the background of astronomical lines limit the sensitivity. The displayed spectrum contains no baseline correction, which shows the excellent stability of the system.

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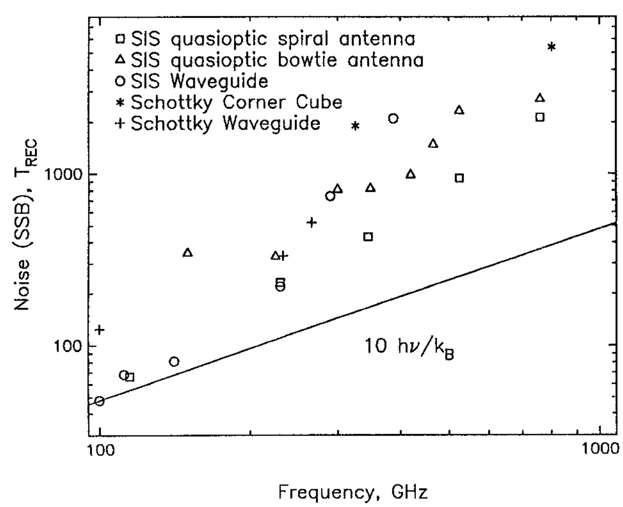

Figure 3 – Comparison of T_{Rec} of the best SIS and Schottky receivers reported in the literature with the spiral antenna receiver. For better comparison all double sideband (DSB) noise temperatures have been converted to single sideband noise temperatures by multiplication by two. The $10h\nu/k_B$ line corresponds to ten times the quantum noise limit, which is about the best currently achievable for these receiver systems. (2,6,12,20,21,22,23,24,25,26)

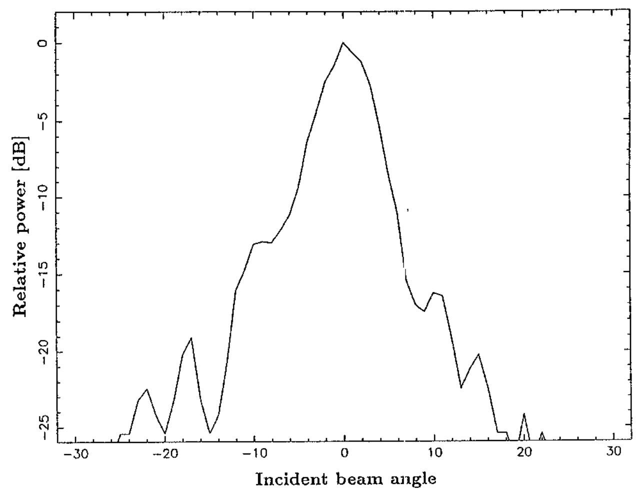

Figure 4 – Spiral antenna mixer *H*–plane beam pattern at 1 mm wavelength.

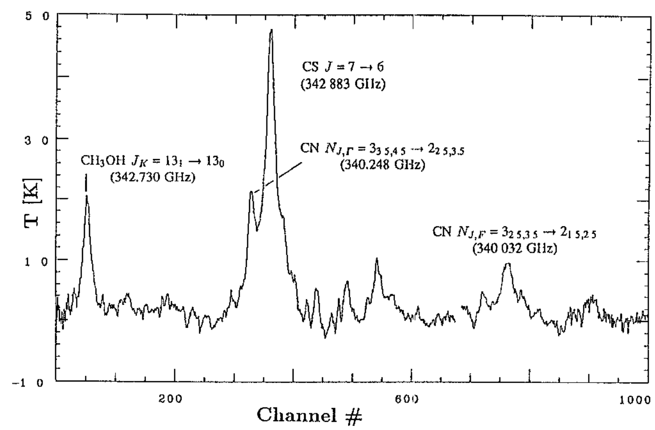

Figure 5 – 341.54 GHz spectrum of the core of OMC1. Response in both sidebands (centered at 342.94 GHz and 340.14 GHz) is included. The total integration time was 3.5 hours and the spectrum is confusion limited, *i.e.* essentially all features are real.

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