A Broad-Band Low-Noise SIS Receiver for Submillimeter Astronomy

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***Abstract*—A quasi-optical 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, and its performance compared with a theoretical model. Noise measurements were made in the laboratory at frequencies between 115 GHz and 761 GHz, yielding double sideband (DSB) noise temperatures ranging from 33 K to 1100 K. The receiver has also been used for astronomical spectroscopy on the Caltech Submillimeter Observatory (Mauna Kea, Hawaii) at 115, 230, 345, and 492 GHz.**

I. Introduction

AMONG THE heterodyne receivers with large instantaneous bandwidths, those using superconductor–insulator–superconductor (SIS) tunneling junctions as the detector are the most sensitive for millimeter-wave radiation [1]–[3]. The most common design for millimeter-wave heterodyne receivers used in radio astronomy is based upon waveguide structures which couple the radiation to the detector. Waveguide structures typically yield a tuning range of about 30 percent [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 backlash and mechanical wear.

An alternative to the waveguide structure is to mount the detector at the center of a planar microantenna which provides quasi-optical 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 quasi-optical 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, covering 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 show no single main beam in the desired direction, perpendicular to the antenna plane, 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.

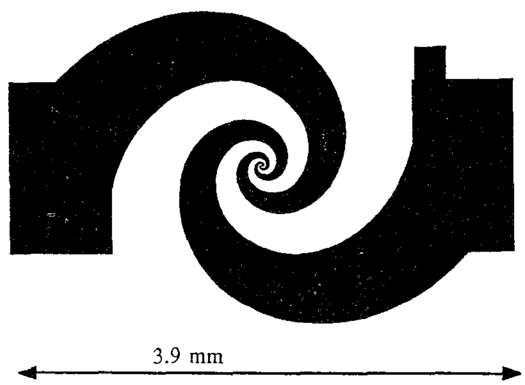

Fig. 1. The planar two-arm logarithmic spiral antenna with the IF ports (contact pads to the left and right).

We have built a new receiver based on the same principles, using a planar two-arm logarithmic spiral antenna (Fig. 1) rather than a bow-tie. In addition to frequency-independent impedance, and nearly symmetric *E*- and *H*-plane patterns, these antennas have frequency-independent beam patterns, with a main beam perpendicular to the antenna plane [9]. Extensive beam shape measurements show that the side lobes are about 20 dB lower than 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 were made between 115 and 761.4 GHz. In addition to the laboratory measurements, this receiver has been tested at 115, 230, 345, and 492 GHz at the Caltech Submillimeter Observatory (CSO) on Mauna Kea, Hawaii. As far as we know, this is the first SIS quasi-optical receiver to have been successfully operated for submillimeter-wave astronomy.

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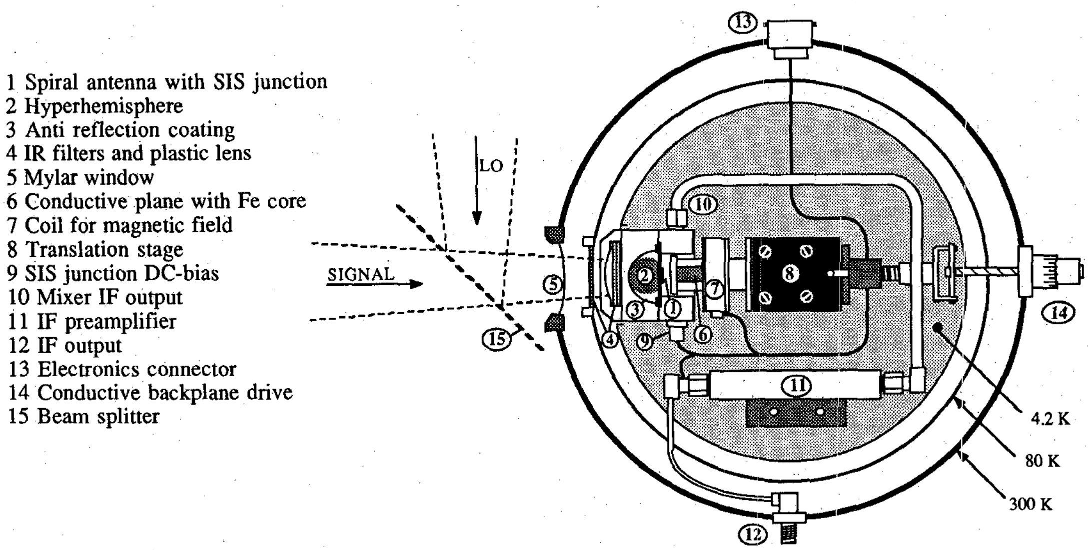

Fig. 2. Receiver layout.

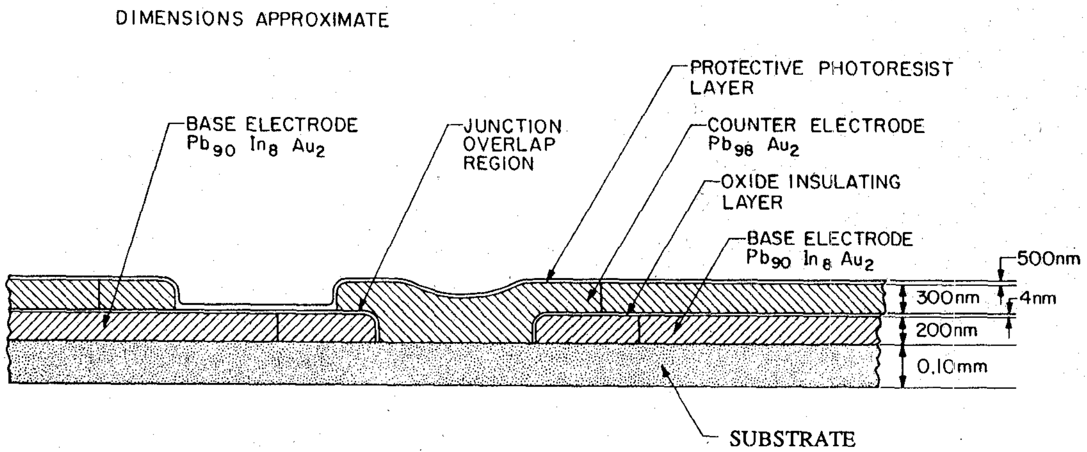

Fig. 3. Section through SIS junction produced with the trilevel photoresist stencil technique.

II. Receiver Description

The overall layout of the receiver is shown in Fig. 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 at AT&T Bell Labs. Standard electron beam lithography for the masks and the trilevel photoresist stencil technique [10], [11] were used for the fabrication of the devices [12] (Fig. 3). A scanning electron micrograph of a junction is shown in Fig. 4. With the SIS junction mounted in the receiver, a gap voltage of 2.40 mV and a critical current density of 7000 A/cm^2 at a junction temperature of 4.2 K were measured. The current–voltage characteristic of a typical junction is shown in Fig. 5. The junction overlap area is about 0.5 μm^2, which yields a capacity of about 10 fF. With a normal state resistance of 50 Ω 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 0.1 mm thick.

B. Sprial Antenna

The planar two-arm logarithmic spiral antenna[1] (Fig. 1) belongs to a family of frequency-independent antennas for which characteristics such as impedance and beam pattern 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, in terms of ratios (logperiodic antennas) or angles (spiral antennas). The shape for a single arm of a planar spiral antenna is given by

$$r = r_0 e^{c\theta} \tag{1}$$

with (r, θ) polar coordinates and c a dimensionless constant (r_0 = "one length unit"). Scaling this with wavelength

$$\frac{r}{\lambda} = \frac{r_0 e^{c\theta}}{\lambda} = e^{c(\theta - \theta_\lambda)} \tag{2}$$

[1]This is also referred to as a two-arm equiangular spiral antenna.

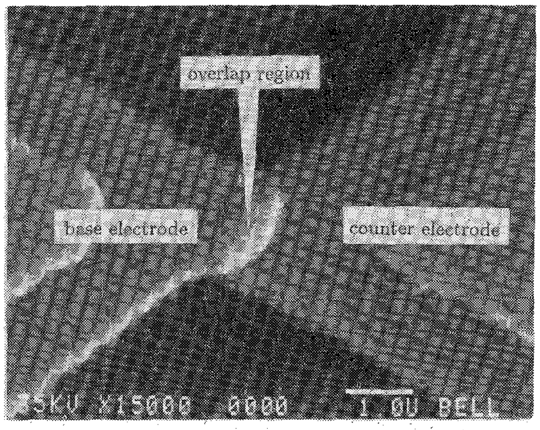

Fig. 4. Scanning electron micrograph of a SIS junction. The overlap area is about 0.5 μm^2 in size.

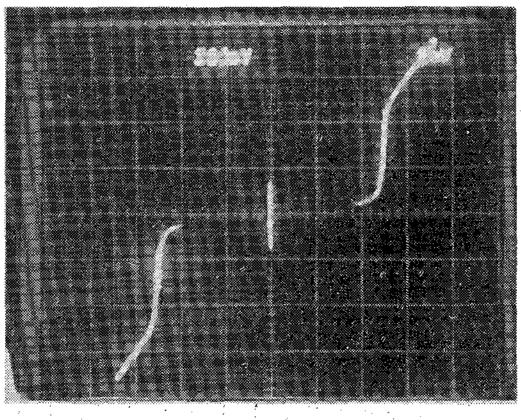

Fig. 5. Current–voltage characteristic of our SIS junction measured with the junction mounted in the mixer block at 4.2 K. The gap voltage is about 2.4 mV. The vertical scale is 20 μA/div and the horizontal 1 mV/div.

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 $\lambda \leqslant R$. 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 $Z_0 = 60\pi\Omega \simeq 188$ Ω. Mounting such an antenna on to a half-space of dielectric (approximated by the hyperhemisphere) yields an antenna impedance of

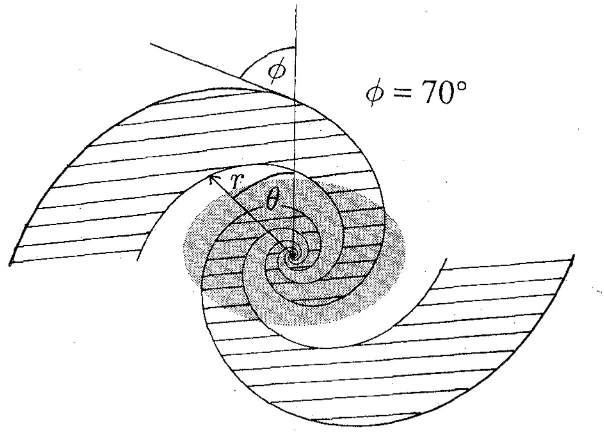

Fig. 6. A sprial arm intersecting with a radial line from the center of the antenna at angle ϕ. The active region of the spiral antenna (about one wavelength in dimension) is shaded, showing the eccentricity of the antenna's effective aperture. An increase of ϕ will decrease the eccentricity, but also decrease the effective aperture.

$$Z_{\mathrm{ant}} = \frac{Z_0}{\sqrt{(1+n_h^2)/2}} \simeq 114\ \Omega \tag{3}$$

where $n_h = 2.11$, the refractive index of single-crystal quartz in the submillimeter region [15].

The dimensionless constant c in (1) and (2) determines the angle ϕ under which a radial line from the center of the antenna intersects with a sprial arm (Fig. 6). They are related through

$$c = \cot\phi. \tag{4}$$

We chose $\phi = 70°$, yielding $c = 0.364$. A more tightly wound spiral, with larger ϕ, will yield a more symmetric beam pattern, since the asymmetry is caused by the rapidly decaying fields (Fig. 6). However, the effective aperture will decrease, resulting in a wider beam. This causes more problems in the RF optics which match the beam from the telescope to the spiral antenna. Our choice for ϕ represents a compromise between these effects, yielding an $f/0.87$ beam at -10 dB relative to the peak, with an eccentricity of less than 1.3.

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 a 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 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, of radius $r = 6.35$ mm, converts the $f/0.87$ beam from the spiral antenna to an $f/2$ beam. Data obtained from a ray-tracing simulation (Fig. 7) show

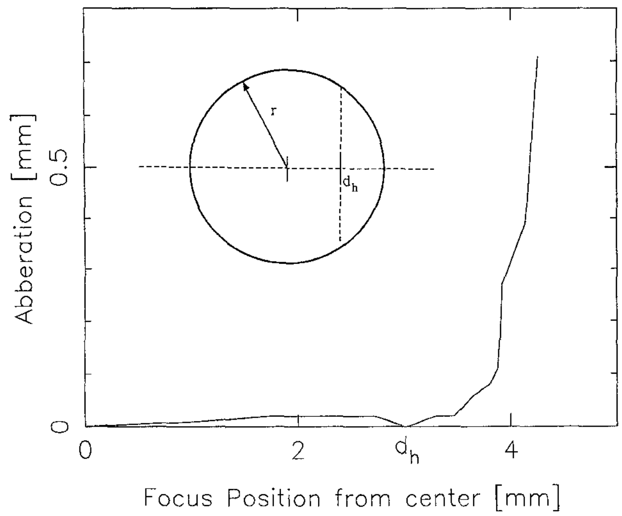

Fig. 7. Aberrations for different positions along the optical axis of a hyperhemisphere. At a distance of $d_h = r/n_h = 3.01$ mm from the center of the hyperhemisphere there are no aberrations.

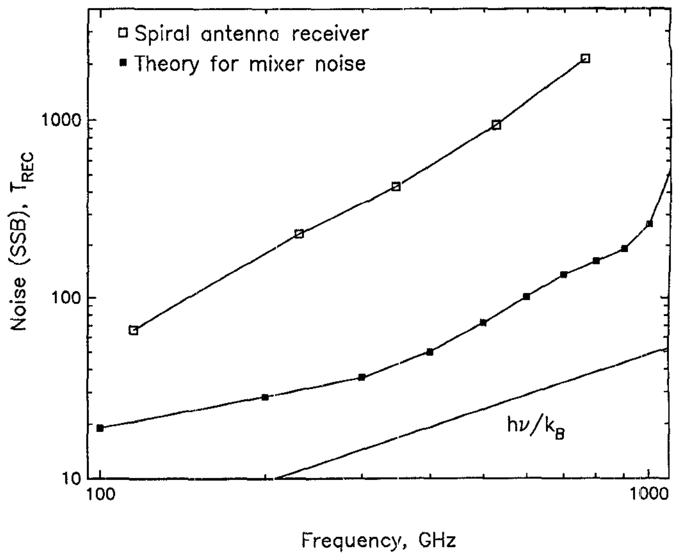

Fig. 8. Comparison of a theoretical prediction for noise temperature, based on the $I-V$ characteristic of our SIS junction, with the measured noise temperature of our receiver. The quantum limit is also shown.

the aberrations of geometrical rays leaving the spiral antenna, centered on the optical axis, with an $f/0.87$ beam. If the antenna is placed at $d_f = r/n_h = 3.01$ mm from the center of the lens, there are no aberrations. Since the antenna has an effective aperture of about one wavelength, there will be some aberrations due to off-axis rays. However, the size of the diffraction disk is much larger than the size of the aberrations, which makes them insignificant.

Kasilingam and Rutledge [16] showed that, for hyperhemispherical lenses with a diameter of more than two free-space wavelengths, the focusing gain in the focal plane decreases by about a factor of 2 for a distance of 0.15 λ off axis. The focusing gain on axis at d_f is $\epsilon_h^2 = 19.8$. The alignment of the center of the planar antenna with the optical axis of the hyperhemispherical lens must be within at least $\lambda/20$.

The $f/2$ beam from the hyperhemisphere is finally matched to an $f/4$ beam from the telescope optics with a plastic lens on the 4 K stage.

Radiative heating of the SIS junction, mainly from infrared radiation, can significantly decrease the mixing performance of the SIS junction. A higher junction temperature will decrease the gap voltage, resulting in more mixer noise. A fused quartz filter, antireflection coated with polyethylene, on the 80 K stage reduces the thermal load for the helium stage. A series of fused quartz and fluorogold scattering filters, cooled to 4 K, were used to reject wavelengths below 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, and the other one leads to 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 cutoff has been set 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 [17], 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.

TABLE I

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

III. Results

Table I 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 CSO. A Gunn oscillator and a Schottky diode multiplier [18] 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 [19]. A conversion loss for the mixer could not be measured precisely, since the matching between the mixer and the IF amplifier and the losses in the optics are not well known. However, at 345 GHz the conversion loss is estimated to be about 11 dB. At 115 GHz an IF saturation of about 10 percent was present, but at higher frequencies no RF or IF saturation was seen, due to high conversion losses.

A theoretical treatment of noise temperature versus frequency [20] is compared to our receiver's performance in Fig. 8. For reference the quantum limit is also shown. The current–voltage characteristic of our SIS junction, which enters the theoretical prediction of the mixing performance, was shown in Fig. 4. The curves for the spiral

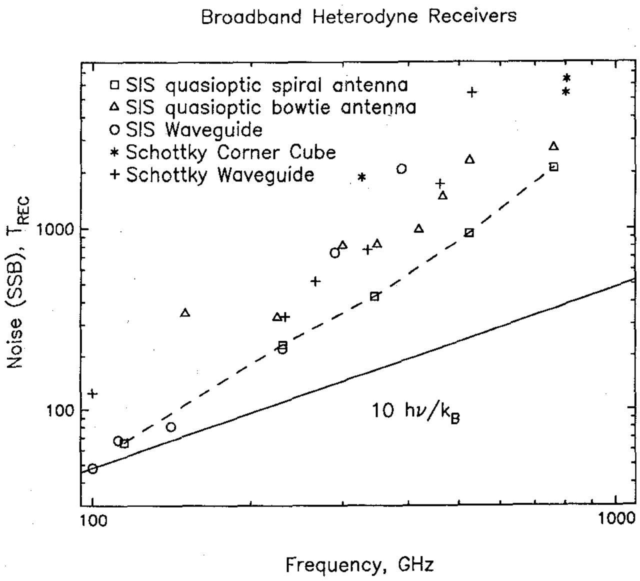

Fig. 9. Comparison of T_{Rec} of the best SIS and Schottky receivers reported in the literature with the spiral antenna receiver. For better comparison all double sideband (DSB) noise temperatures have been converted to single sideband noise temperatures. The $10h\nu/k_B$ line corresponds to ten times the quantum noise limit, which is about the best currently achievable for these receiver systems [2], [6], [12], [22]–[30].

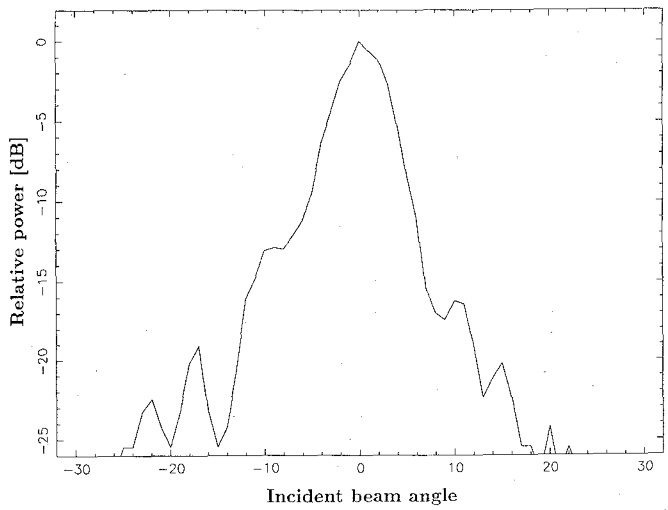

Fig. 10. Sprial antenna mixer beam pattern at 1 mm wavelength, measured outside the dewar in the H plane of a linearly polarized transmitter.

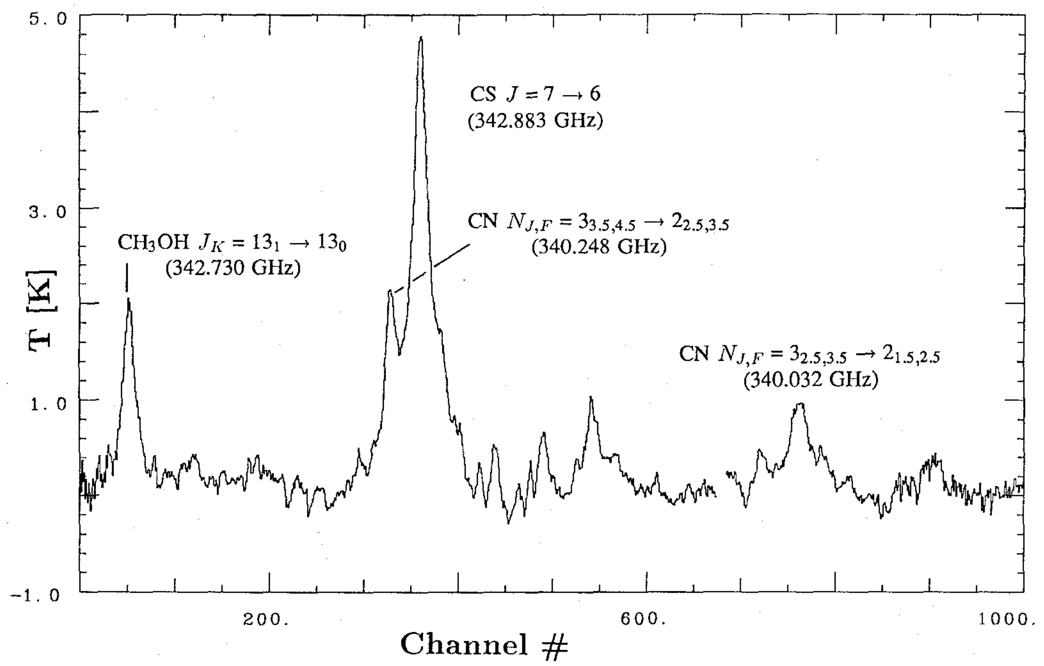

Fig. 11. 341.54 GHz spectrum of the core of OMC1. Response in both sidebands (centered at 342.94 GHz and 340.14 GHz) is included. The total integration time was 3.5 hours and the spectrum is confusion limited; i.e., essentially all features are real.

antenna receiver's performance and the theoretical mixer noise are similar, but the measured points are shifted with respect to the theoretical prediction. We attribute the shift to losses in the optics, additional noise from the preamplifiers, and mismatch of the SIS junction to the antenna, due to the junction's capacitance. The curve for the theoretical mixer noise is a prediction, assuming optimum matching conditions for the SIS device.

Fig. 9 shows a comparison of the spiral antenna receiver with a bow-tie antenna receiver, state-of-the-art SIS waveguide, and Schottky receivers. Fig. 10 shows a typical beam pattern taken at $\lambda = 1$ mm with the spiral antenna receiver. The measurement was performed in the H plane of a linearly polarized transmitter outside of the dewar. The side lobes are probably due to diffraction of the beam at the dewar windows, since scale-model measurements of the antenna alone do not show them [21]. 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 beam efficiency at 345 GHz was about 30 percent, which is lower than expected by a factor of 2 or 3. This was attributed to a focusing problem inside the mixer block, which has now been rectified. Spectra with the rectified RF optics have been taken, yielding about 87 percent beam efficiency at 230 and 345 GHz. Fig. 11 shows a spectrum of a molecular cloud in the Orion region (OMC1) at 341.54 GHz LO frequency taken with the old RF optics. The acousto-optical spectrometer has a center frequency of 1.4 GHz, and responds to both sidebands, which are centered at 342.94 GHz and 340.14 GHz. The integration time was 3.5 hours. The spectrum is confusion limited; i.e., the background of astronomical lines limits the sensitivity. The displayed spectrum contains no baselinecorrection, showing the excellent stability of the system.

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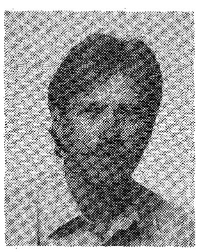

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From 1978 through 1980, Dr. Wengler worked at Bell Labs on cooled Schottky-diode mixers for 3 mm radio astronomy. From 1980 through 1987, he worked at Caltech on many aspects of superconducting diode (SIS) heterodyne receivers. He developed the first quasi-optical SIS mixer for submillimeter wavelengths. He worked on millimeter SIS mixers for Caltech's Owens Valley Radio Observatory. He has worked extensively with the quantum heterodyne theory describing SIS mixers, both analytically and computationally. His current research interests include submillimeter receivers and oscillators, superconducting electronics, high-temperature superconducting devices, and investigations of "squeezed" states of the quantum radiation field using SIS detectors.

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After one year at Stanford University, he returned to Oxford for two years and then moved to Bell Telephone Laboratories Physics Research Laboratory at Murray Hill, NJ. There he developed techniques for millimeter- and submillimeter-wave detection for astronomy. In 1975 he spent one year at London University as University Reader in Physics. In 1980 he joined the faculty of Caltech as Professor of Physics. At Caltech he took on the task constructing the Owens Valley Radio Observatory millimeter-wave interferometer, as Associate Director of the Observatory. In 1982 he became Director Designate for the Caltech Submillimeterwave Observatory, to be constructed in Hawaii, and in 1986, on successful completion of the construction, became Director. His current research interests are in molecular and atomic spectroscopy of the interstellar medium and in the development of superconducting devices for submillimeter-wave detection.