85–115-GHz Receivers for Radio Astronomy

D. P. WOODY, R. E. MILLER, AND M. J. WENGLER

Abstract —**Low-noise receivers for radio astronomy have been built using Pb alloy superconducting tunnel junction mixers operating at 4.5 K. They have been used for 85–115-GHz astronomy with double-sideband receiver noise temperature between 70 and 200 K. Junction fabrication and receiver construction, operation, and performance are described herein.**

I. Introduction

THE FIRST REPORTS of heterodyne mixing in superconductor–insulator–superconductor (SIS) tunnel junctions using quasiparticle effects indicated that they would make excellent low-noise millimeter-wave receivers [1], [2]. The theory of quantum mechanical mixing in quasiparticle tunnel junctions which describes the operation of these devices indicated that the mixer noise temperature should approach the quantum limit hf/k_B where h is Planck's constant, k_B is Boltzmann's constant, and f is the signal frequency [3]. At 100 GHz, the quantum limit is 4.8 K. This theory also predicted that quasiparticle SIS mixers would not be limited by having conversion loss as are classical mixers but should be capable of achieving large conversion gain [4] and thus greatly decreasing the IF amplifier's contribution to the total system noise. The predicted excellent performance and the success of the first tests of a complete SIS receiver [5] indicated that these receivers would be very useful for millimeter-wave astronomy. A review of many of the important aspects of SIS receivers for radio astronomy has been given by Phillips and Woody [6].

This paper describes the tunnel junction receivers which were developed for the Owens Valley Radio Observatory (OVRO) Millimeter Interferometer. They use a simple circular waveguide mixer block, Pb alloy junctions, and are cooled using a commercial 4.5-K closed-cycle refrigerator. These receivers are in routine operation over the frequency range from 85 to 115 GHz and have achieved double-sideband noise temperatures of 100 K with IF bandwidths greater than 250 MHz. We have had more than four years of experience using SIS receivers for radio astronomy and have found them to be reliable and well suited to a large variety of astronomical observations. The receivers have been used for continuum and line observations and for both linked interferometry and very long baseline interferometry.

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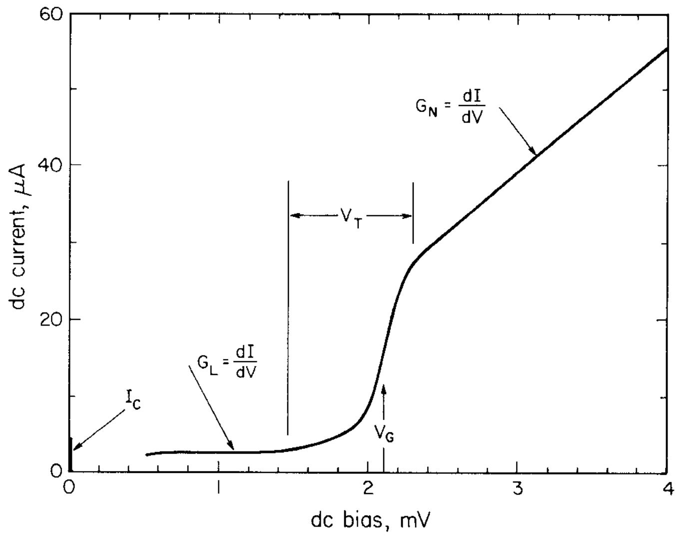

Fig. 1. Typical dc $I-V$ characteristic of a PbInAu junction at 4.5 K. The normal state conductance, "leakage" conductance, transition width at the gap voltage, and Josephson supercurrent are labled G_N, G_L, V_T, and I_C, respectively.

II. SIS Junctions

A junction must satisfy several different criteria if it is to be used in a practical receiver. It must have the electrical characteristics necessary to make a good mixer. It must also be stable and rugged enough to survive normal handling and be packaged in an easy to use structure. The basic structure of an SIS tunnel junction is simply a superconductor–insulator–superconductor sandwich. The physical process in use here is the tunneling of quasiparticles (single electrons as opposed to superconducting pairs) through the insulating barrier. The mixing properties of the junction are determined by its dc $I-V$ curve [7]. The dc $I-V$ curve in turn is dependent upon the superconducting alloys and dielectric used to form the tunnel junction. The electrode and insulating materials along with the fabrication process also determine the stability and ruggedness of the junction. The embedding network nearest the junction depends upon the electrode geometry, size of the junction, and the substrate material.

Heterodyne performance can be calculated from the dc $I-V$ curve using the quantum mechanical theory of mixing developed by Tucker [7]. It is not necessary, though, to perform detailed calculations to evaluate the suitability of a particular junction for use in a mixer. A typical $I-V$ curve for one of our Pb alloy junctions at 4.5 K is shown in Fig. 1. The curve can be conveniently divided into three

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parts: the region above the gap voltage V_G with approximately linear conductance G_N, the region below the gap with roughly linear "leakage" conductance G_L, and the transition from G_L to G_N of width V_T. The three parameters G_N, G_L, and V_T qualitatively determine the mixing characteristics of an SIS junction. The discontinuities and features which are apparent near the origin arise from the tunneling of superconducting pairs and the Josephson effect. This region is not treated by simple quasiparticle mixer theory and is often associated with a large excess noise. This becomes a serious problem for small capacitance junctions operating at RF frequencies greater than about half of the gap energy, $hf > eV_G/2$.

G_L is equivalent to a lossy element in parallel with the device and thus the normalized "leakage" $g_L = G_L/G_N$ must be kept to a minimum. Tucker's theory reduces to that of a classical resistive mixer in the limit $hf/e \ll V_T$ [7]. Thus, we must have $V_T < hf/e$ if we are to achieve the high conversion efficiency or gain which is possible with these quantum mixers. A junction satisfying $V_T < hf/e$ is well approximated by an ideal junction ($G_L = 0, V_T = 0$) with normal state conductance $G'_N = G_N - G_L$ in parallel with its fixed capacitance and a shunt conductance G_L. The impedance at a particular port of the mixer depends upon the terminations at all of the other ports but will be proportional to $R_N = G_N^{-1}$. The signal impedance is typically somewhat less than R_N while the IF impedance is equal to or larger than R_N. Thus, a good SIS junction will have a narrow transition region from G_L to G_N ($V_T < hf/e$), low "leakage" ($g_L < 0.1$), and an impedance which is convenient for matching to the RF and IF circuits ($20 < R_N < 200\ \Omega$).

We have used both PbInAu and PbBi alloys for the junction electrodes. The insulating dielectric is formed by oxidizing the bottom electrode. These alloys were chosen as a compromise between pure superconducting metals which exhibit excellent $I-V$ characteristics but don't survive thermal cycling and more heavily alloyed systems which are very stable but have inferior $I-V$ characteristics [8].

The sandwich structure of the junction gives rise to a capacitance in shunt across the junction. The magnitude of this capacitance is set by the junction area and the thickness and dielectric constant of the insulating barrier. The electrodes are superconducting and thus an arbitrarily large capacitance can in theory be tuned out, but only over a limited bandwidth. The capacitance should be kept small for broad-band operation and to decrease the necessary Q of the tuning circuit. Lead alloy junctions with oxide insulating barriers typically have a capacitance of ~ 0.04 pF/μm^2 [8] and thus an 80-Ω junction with an area of 0.5 μm^2 will have $2\pi fRC \approx 1$ at 100 GHz.

The devices are fabricated on 0.1-mm-thick polycrystalline quartz substrates using a photolithographic bridge structure technique. This is a variation of the tri-level stencil technique developed by Dunkleberger [9] and adapted by Dolan [10] for fabricating small-area tunnel junctions. The tri-level stencil consists of a 1.5-μm bottom photoresist layer which is uniformly exposed, a 3-nm aluminum buffer film, and a 0.75-μm top photoresist layer which is exposed through a patterned mask. The exposed area of the top photoresist layer is developed away, the aluminum buffer layer etched through, and the bottom photoresist developed to undercut the top layer by 1 μm. Unexposed areas in the top layer which are less than 1 μm wide are completely undercut. This allows fabrication of structures in the photoresist which consist of bridges of photoresist suspended above the substrate. Fig. 2 is a picture of one of the bridge structures used to make SIS tunnel junctions. The bridge is defined by contact UV exposure through a chromium mask. The mask is made using electron-beam writing and can be re-used many times.

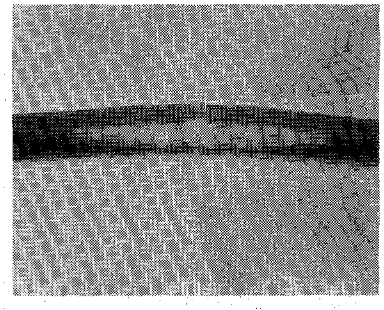
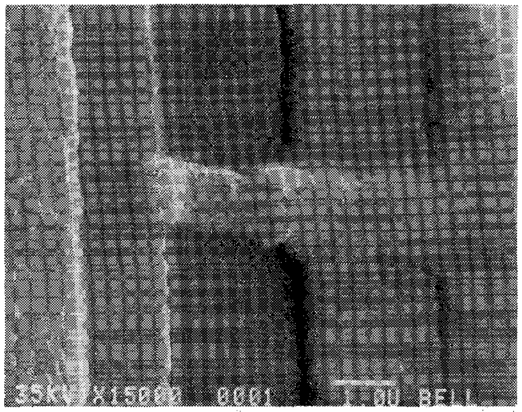


Fig. 2. An SEM photograph of the photoresist bridge structure used to fabricate small-area tunnel junctions.

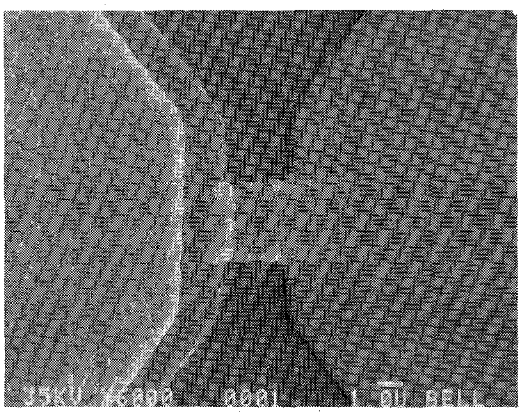
The deposition of the base electrode, oxidation of this electrode to form the insulating layer, and deposition of the counter electrode are all done without breaking the vacuum in the evaporator. The base electrode for PbBi junctions is formed by sequentially evaporating 0.02 μm of In and 0.2 μm of $Pb_{90}Bi_{10}$ to completion from one side of the bridge. This is exposed to an O_2 discharge for an empirically determined length of time to give the desired current density in the resulting junction. The counter electrode is formed by evaporating 0.2-μm of $Pb_{90}Bi_{10}$ to completion from the other side of the bridge. A PbBi alloy junction is formed by the overlap of the two electrodes beneath the suspended photoresist bridge. The excess metal is lifted off the substrate by dissolving the underlying photoresist in acetone. For PbInAu junctions, the base electrode consists of 0.2-μm $Pb_{90}In_{08}Au_{02}$ alloy and the counter electrode consists of 0.3-μm $Pb_{96}Au_{04}$ alloy. It is assumed that the evaporated metals diffuse at room temperature to form nearly uniform thin-film alloys. The junctions are protected with 0.4 μm of photoresist. The wafer is then cut into 0.25×1.78 mm chips. Fig. 3 is an SEM picture of two junctions.

The junction area is determined by the bridge length and width (1×1 μm), its height above the substrate (1.5 μm), and the relatively coarse adjustment of the two electrode evaporation angles. Hundreds of chips with similar junction properties can be fabricated on the same wafer or a range of junction areas, and thus resistances, can be made by using a mask with several different bridge outlines.

The junctions fabricated in this way are well suited for millimeter and submillimeter mixers. They have normal



(a)



(d)

Fig. 3. SEM pictures of Pb alloy tunnel junctions: (a) is $\sim 0.5 \times 0.5$ μm and is near the limit of what can be easily fabricated using this technique, (b) is $\sim 1.0 \times 2.0$ μm.

state resistances in the range from 20 to 200 Ω and a capacitance of $\sim$ 0.02 pF. These junctions have been used in receivers operating as high as 380 GHz [11]. Their "leakage" is typically in the range from $g_L = 0.08$ to 0.15 at 4.5 K. They are reasonably stable and have survived storage in dry air at room temperature for as long as twelve months with little change. They should survive indefinitely at liquid-nitrogen temperatures. The failure rate on thermal cycling to liquid-helium temperatures is less than 10 percent. This is sufficient to allow measurement of the $I-V$ curve in liquid helium before mounting in the mixer block and still survive periodic warm-ups.

III. Receiver Configuration

Four complete 100-GHz SIS receiver systems have been built for use in the OVRO millimeter-wave interferometer. Several different mixer block designs and cooled first-stage IF amplifiers have been used, but all the receivers have the same basic configuration. The receiver configuration is diagramed in Fig. 4. The principle parts are the local oscillator system, feedhorn, mixer block with backshort, and the IF amplifier chain. Three of the receivers are cooled to 4.5 K by closed-cycle refrigerators [12] and the fourth is cooled to 4.2 K in a liquid-helium cryostat.

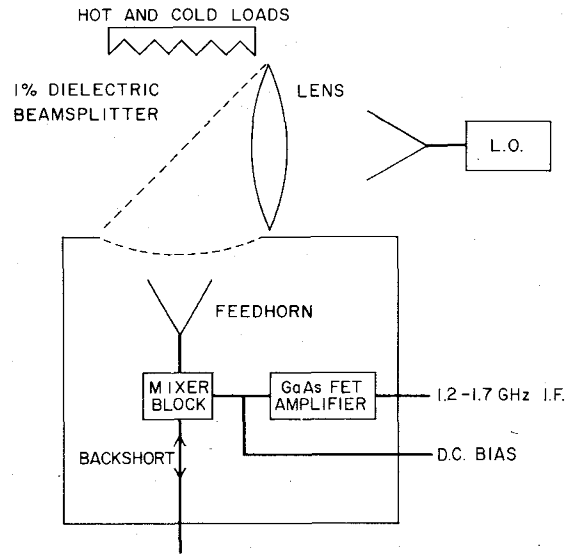


Fig. 4. Schematic diagram of the OVRO SIS receivers. The feedhorn, mixer block, and IF amplifier are all cooled to 4.5 K.

The LO power requirements for SIS mixers are very small. A mixer utilizing a single junction requires $\sim (hf/e)^2/R_N$ of absorbed LO power. This is only a few nanowatts at 100 GHz. Even allowing for large mismatches and <1-percent coupling of local oscillator power from the source to the mixer, only a few microwatts of power are required from the LO source. The LO sources used for the receivers at the OVRO millimeter interferometer are Gunn oscillators in the 50-GHz range doubled to ~ 100 GHz using a commercial doubler [13]. This is coupled via a 0.1-mm-thick mylar beamsplitter, which reflects ~ -26 dB of the incident TM polarized LO into the mixer.

The feed is a scalar horn designed to operate from 90 to 115 GHz with a 30° included angle at the -13-dB taper. The design is based upon the standard formulas given by Thomas [14]. This is machined directly from aluminum and its beam pattern was measured at 115 and 90 GHz and found to be satisfactory. The horn is attached directly to the cooled mixer block. A $\lambda/2$ crystalline quartz window in the 60-K radiation shield is used to block the infrared radiation.

The theory of SIS mixers indicates that a broad range of embedding network impedances will yield excellent receivers (noise temperature <100 K) [6] so that it is only necessary to avoid large parasitics or extreme impedance transformations. Presumably, mixers with noise temperatures close to the quantum limit will require an optimized embedding network. The mixer blocks we use all have the quartz chip supporting the junction mounted across the waveguide parallel to the E-field. One end of the junction is grounded to the waveguide wall and the dc bias and IF signals are brought out through an RF choke structure in the opposite wall. A sliding backshort provides the only RF tuning. Rectangular waveguide with aspect ratios of 2:1 and 8:1 and circular waveguide have been used. The circular waveguide mixers have produced the best receivers and will be described in more detail below.

The circular waveguide mixer block is designed for ease of fabrication. Fig. 5 is a cutaway drawing of the block. It utilizes circular waveguide 2.4 mm in diameter ($f_C = 74$ GHz) milled into OFHC copper. The waveguide is multimoded at 115 GHz, but it is expected that only one polarization of the TE_{11} mode is well coupled to the junction because of the symmetry of the mounting structure. The junction is suspended between two copper posts which extend into the waveguide from opposite sides. The posts have a "D" cross section in the waveguide. The chip containing the junction is placed across the posts with the superconducting film side next to the flat part of the posts. Silver paint is wicked between the posts and the chip to provide mechanical support and electrical connection. This geometry keeps the electrical length through the paint to < 25 μm. One of the posts is soldered directly to the waveguide. The other post is made from 0.57-mm-diam copper wire with enamel insulation on it. It is glued into a 0.61-mm-diam hole in the block using 7041 GE varnish and it provides the dc and IF connections. There is a $\lambda/4$-wide slot in the block $\lambda/4$ from the waveguide to act as a high-impedance section in the coaxial RF choke. The diameter of this coaxial line is small enough to allow only the TEM mode to propagate below ~ 120 GHz. The backshort is a choked plunger with the first 0.74-mm-long low-impedance section and the following 0.84-mm-long high-impedance section noncontacting and the shaft of the plunger is a slide fit. It is adjusted by a shaft connected to the outside of the dewar. Note that the feedhorn ends very close to the junction plane so that there is virtually no waveguide in front of the mixing element and the structure can't be accurately analyzed in terms of simple structures in an infinitely long waveguide.

The first-stage IF amplifiers are cooled GaAs FET L-band amplifiers. One of the receivers uses a three-FET amplifier provided by S. Weinreb of the National Radio Astronomy Observatory. The other receivers use a two-FET amplifier developed by E. Sutton for low-power dissipation and is based upon the design of S. Weinreb [15]. These IF amplifiers have noise temperatures in the range from 8 to 12 K over a 500-MHz bandwidth and more than 24 dB of gain. We have also used a cooled isolator [16] between the mixer and IF amplifier to improve the performance under mismatched conditions.

All of the parts are fabricated using standard machining techniques. The simplicity of the design lends itself to scaling to higher frequencies. Sutton has implemented this design in a receiver operating in the range from 180 to 300 GHz [11]. The mixer block and backshort can be scaled to even higher frequencies, but a more sophisticated procedure may be required to fabricate the feedhorn.

IV. Receiver Performance

The SIS receivers have been evaluated on the telescope under normal operating conditions. The primary performance measurement is of the response to hot (290 K) and cold (80 K) loads placed between the receiver feedhorn and the telescope optics. There are three tuning parameters: the backshort position, the dc-bias voltage, and the LO power level. The tuning procedure is straightforward. The backshort is set to maximize the coupling of the LO to the junction by monitoring the bias current at a fixed bias voltage. The bias voltage and LO power are then tuned to give a local maximum in the IF power with the hot load in place. The best performance is obtained when the bias voltage is $\sim 1/2$ of a photon step (hf/e) below the gap V_G. Extensive mapping of the performance versus tuning parameters has shown that this gives the minimum receiver noise temperature for most of the receivers we have tested. The receiver has essentially balanced sideband response when tuned using this method. Single-sideband response can usually be achieved by adjusting the backshort to optimize coupling to the desired sideband. Greater than 10 dB of image rejection has been achieved. The instantaneous bandwidth of the different mixers varies from a few to tens of gigahertz. The bandwidth is reduced as the backshort is adjusted to tuning positions further from the junction.

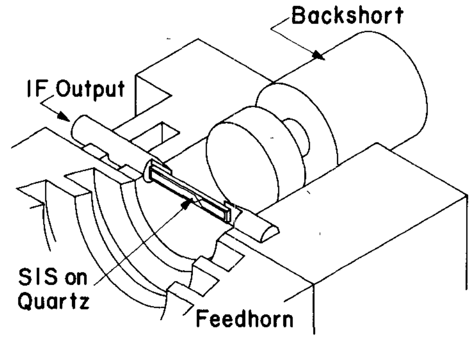


Fig. 5. Cutaway isometric drawing of the 2.4-mm-diam circular waveguide mixer block. Some dimensions are given in the text. The mixer block is solid copper with holes bored for the circular waveguide and IF line and a slot for the high-impedance section of the IF choke. The feedhorn is machined directly from aluminum. The backshort is gold-plated phosphor-bronze.

Receiver and mixer performance are determined from $I-V$ curves and measurements of the IF output power (P_{IF}) with hot (290 K) and cold (80 K) Eccosorb loads held at the mixer input. Fig. 6 shows the data for a receiver with a 95-GHz LO. The P_{IF} was measured in the band from 1250 to 1500 MHz and is calibrated in terms of the equivalent Rayleigh–Jeans temperature at the IF amplifier input. This calibration and also a determination of the IF amplifier added noise are calculated using the linear portions of the $I-V$ and P_{IF} curves. Tunneling of quasiparticles gives rise to shot noise [17]. For a junction biased where the current is a linear function of the voltage, the shot noise power spectral density increases at a rate of $e/2k_B = 5.8$ K per mV. Then, the linear portion of the P_{IF} curve must have a slope of 5.8 K per mV when referred to the IF amplifier input. The linear portion of the $I-V$ extrapolates to zero at 0.6 mV. Then, an extrapolation of the linear portion of the P_{IF} curve back to 0.6 mV determines the noise power added by the IF amplifier to be 11.7 K referred to its input. In this way, the noise added by

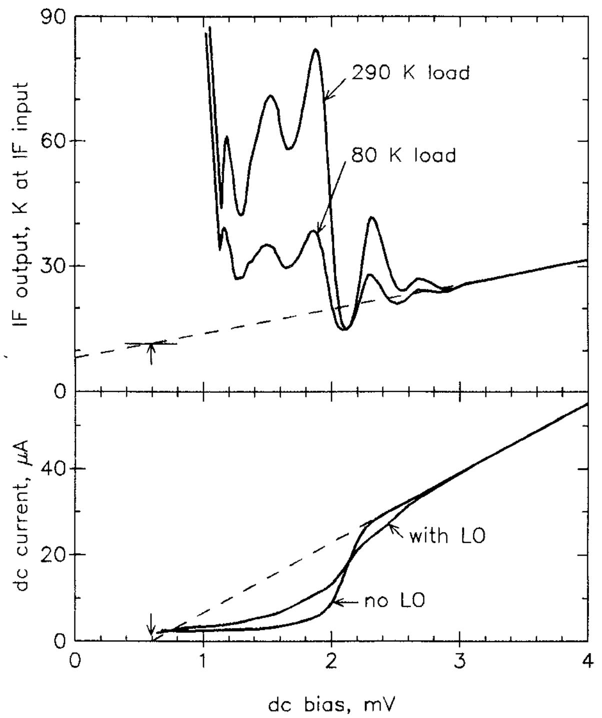


Fig. 6. $I-V$ and IF power versus dc voltage bias for a typical receiver with 95-GHz LO applied. The $I-V$ with no LO is also shown. The IF power curves are taken with hot (290 K) and cold (80 K) loads in front of the feedhorn. The dashed lines extrapolate the linear portions of the $I-V$ and the IF power curves. The current extrapolates to zero at 0.6 mV. These are used to determine receiver and IF amplifier performance as described in the text.

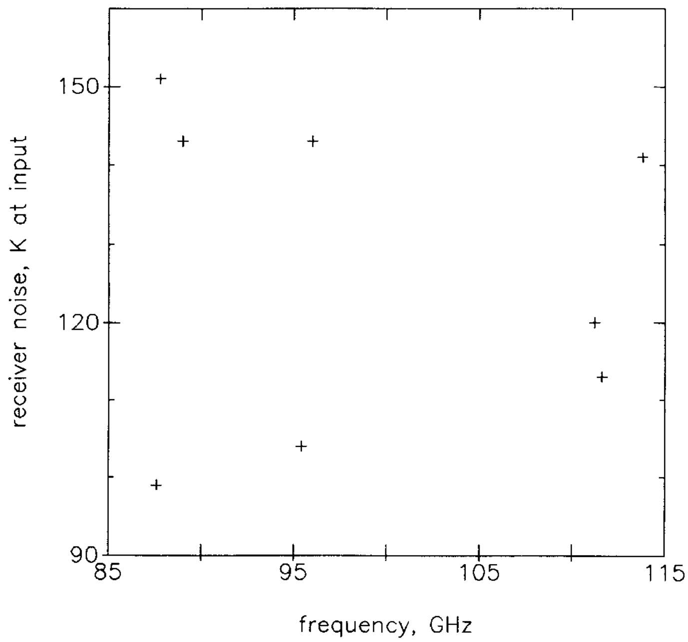


Fig. 7. Noise temperature of one of the better receivers as measured during astronomical observations. The measurements were made using hot and cold loads in the telescope beam transport path. The noise temperature is given as double sideband but often the receiver was actually operating with a signal-to-image ratio greater than four, so that the single-sideband noise temperature is much less than twice the double-sideband values plotted.

the IF amplifier is calibrated for IF source admittances equal to G_N. A frequency down conversion efficiency of $44/210 = -6.8$ dB and a mixer temperature of 4.8 K can be calculated, since the dynamic conductance at 1.9 mV with LO applied is close to G_N. The total receiver noise referred to its input is therefore 105 K.

The receiver performance is monitored at the various frequencies used for astronomical observations. The hot- and cold-load measurements consistently yield double-sideband noise temperatures between 100 and 200 K over the frequency range from 85 to 115 GHz. The receivers often are actually operating as single-sideband systems so that the single-sideband performance ranges from 100 to 400 K with typical values of 150 to 250 K. The double-sideband noise temperature of one of the better receivers is plotted in Fig. 7. The best noise temperature achieved to date is 70 K double-sideband at 114 GHz.

Tunnel junctions made using the same alloys can have a much smaller "leakage" current g_L and a narrower transition width V_T when cooled to 2 K. Thus, we could expect to improve the performance of our mixers by cooling them to 2 K. It is also clear that this simple mixer design does not yield an optimum embedding network for the junction. An optimized mixer circuit would yield a greatly improved system, even at 4.5 K.

V. Conclusions

SIS tunnel junction receivers have proven to be a practical way of achieving the low-noise performance required for radio astronomy. The receivers are easy to construct and operate aside from the state-of-the-art junction fabrication and the complication of cooling the mixer to 4.5 K. The low local-oscillator power requirements make it much easier to generate the local-oscillator power than for other kinds of millimeter heterodyne receivers. The performance we have achieved indicates that excellent receivers can be made using simple mixer structures, although the best performance should approach the quantum limit of hf/k_B and will require optimized mixer designs.

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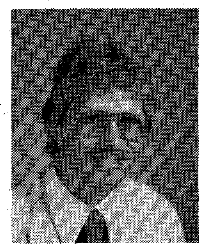
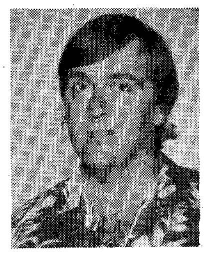


Ronald E. Miller was born in Mechanicsburg, PA, on July 19, 1947. He received the Associate in Applied Science degree from the Williamsport Area Community College in 1969. That same year, he joined the Solid State and Physics of Materials Department of Bell Laboratories, where he is now a Member of the Technical Staff. His main research interest is micron and submicron fabrication of thin-film devices.



Michael J. Wengler was born in Queens, NY, on May 11, 1957. He received the B.A. degree in physics from Swarthmore College, Swarthmore, PA, in 1978. He worked at Bell Labs from 1978 to 1980 on Schottky-diode 115-GHz mixers. Since 1980, he has been a graduate student at Caltech, Pasadena, CA, working on SIS mixer theory and design. He hopes eventually to receive the Ph. D. degree from the Department of Applied Physics at Caltech.

Field Theory Design of Rectangular Waveguide Broad-Wall Metal-Insert Slot Couplers for Millimeter-Wave Applications

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***Abstract*—A design theory for broad-wall metal-insert slot couplers suitable for an inexpensive and very accurate metal-etching manufacturing technique is described. The method of field expansion into suitable eigenmodes used considers the effects of finite insert thickness and higher order mode interaction at the step discontinuities. Computer-optimized design data for −3-dB couplers in the *Ka*- and *W*-bands are given. The data of the *Ka*-band design are transferable into the *U*- and *V*-bands by suitable frequency scaling calculation. Since the metal-etching technique is also advantageously applicable for couplers in the centimeter wavelength range, optimized design data for *E*-plane slot couplers in the often used *Ku*- and R120-waveguide-bands are included in the tables given. A *Ku*-band metal-etched four-slot coupler prototype achieves a ±1-dB bandwidth of the −3-dB coupling of about 2 GHz, together with −36-dB isolation. The measurements show good agreement with theory.**

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I. Introduction

COUPLING BY SLOTS over the whole width of the common broad-wall with minor thickness [1] or thicknesses of about one-quarter guide wavelength ("branch guides") [2]–[15] is an attractive technique to design directional couplers with the potential of wide variation of coupling, directivity, input VSWR, and bandwidth values. Although the Reed [4] coupler type has already been successfully applied at millimeter wavelengths [12]—where the approximately $\lambda_{go}/4$ long branch lines are fabricated by assembling and soldering two suitably milled waveguides—for appropriate coupler designs it may often be desirable, however, to make use of the highly accurate and inexpensive metal-etching technique as has been shown recently as an example of metal-insert filters [16], [17]. This

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