A Superconducting Tunnel Junction Receiver for 230 GHz

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Abstract —**The performance of superconducting tunnel junctions as high-frequency receivers is discussed. Low-noise mixing in superconductor–insulator–superconductor (SIS) quasi-particle tunnel junctions has been seen for frequencies up to 400 GHz. Such mixers have the significant advantage of small local-oscillator power requirements. A receiver has been constructed which has a single-sideband (SSB) receiver noise temperature of 305 K at 241 GHz.**

I. Introduction

Great progress has been made in recent years in the development of sensitive millimeter and submillimeter-wave receivers. Much of this progress has come about due to the needs of radio astronomy, where such receivers are essential for studies of interstellar matter such as carbon monoxide, which has its lowest frequency transitions at 115, 230, and 346 GHz, and atomic carbon (CI) at 492 GHz. Various techniques have been used to exploit this frequency range. One of the earliest successful techniques was the InSb hot-electron bolometer [1], which was used for most of the original astronomical detections at frequencies above 200 GHz. Room-temperature Schottky mixers, with their much greater bandwidths, have also been very important, particularly at the lower frequencies [2], [3]. Currently, some of the best receiver systems being developed and in use are cooled Schottky-diode mixers [4], with their greatly reduced noise temperatures compared with the room-temperature mixers. An attractive alternative throughout this frequency range and one which is currently under development is the superconductor–insulator–superconductor (SIS) quasi-particle mixer [5].

The SIS mixer is a form of superconducting tunnel junction in which electrons tunnel between two superconductors separated by a thin oxide barrier. These electrons can tunnel either as pairs via the Josephson effect or as individual quasi-particles. Although early work concentrated on Josephson mixing [6], much recent attention has been devoted to heterodyne mixing using the nonlinear quasi-particle current–voltage ($I-V$) characteristic [7]–[12]. In addition to their usefulness as low-noise receivers, these devices are of interest as examples of quantum-mechanical mixers [13]. Because the photon energy may be comparable with the energy scale of the tunneling nonlinearity, these junctions can exhibit unique quantum-mechanical effects. Among these is the potential for conversion gain, an effect which is forbidden for classical resistive mixers but seen in SIS mixers [14], [15]. Additional advantages of quasi-particle mixers include their low-noise performance and their small local-oscillator power requirements. Although most work done to date with SIS mixers has been at comparatively low frequencies (18–115 GHz), they exhibit considerable promise for use as receivers at considerably higher frequencies, where it is still difficult to obtain sensitive receiver systems.

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II. Receiver Design

A. High-Frequency Limitations

Most work which has been done so far with SIS mixers has been done in the low-frequency regime, below about 100 GHz. In this limit, the frequency of operation is much smaller than that corresponding to the superconducting energy gap ($2\Delta/h$). At such frequencies the sharpness of the $I-V$ characteristic and the amount of excess current present below the gap are thought to be the principal factors determining the conversion efficiency and noise properties of the device.

Relatively little investigation has been made of the upper frequency limitation of SIS mixers. It has been clear that above about 100 GHz the Josephson effect begins to interfere with optimal operation of the mixer. A rough upper frequency limit of 200 GHz has been suggested [16] for single-junction SIS mixers based on experience at somewhat lower frequency. While this does not represent a firm upper limit, it is clear that success at higher frequency operation is intimately connected with success at understanding and suppressing the Josephson-effect-related phenomena. Consideration of just single-particle effects indicates that efficient mixing could occur for frequencies up to $\nu = 4\Delta/h$, which is approximately 1200 GHz for Pb-alloy junctions. Pair breaking, which has an onset at $\nu = 2\Delta/h$, may limit operation to more like 600 GHz. However, the results of Danchi *et al.* [17] are encouraging since they observe quasi-particle and Josephson steps at frequencies well above $2\Delta_{Sn}/h$ for Sn–SnO–Pb junctions.

B. Josephson-Effect Structure

Josephson-effect mixing obeys the same general formalism as quasi-particle photon assisted tunneling except that mixing is provided by the singularity of the dc Josephson effect at $V=0$. This effect may be used to construct mixer–receivers although it has generally proved too unstable for practical use. In the presence of applied RF, the dc $I-V$ curve is modified by the introduction of current singularities at voltages displaced from zero volts by $V = nh\nu/2e$, that is, a spacing half that of the quasi-particle tunneling steps. The strength of these singularities is given by Bessel functions of argument $\alpha = 2eV_1/h\nu$, where V_1 is the applied RF voltage. Since α must be of order unity in order to get significant quasi-particle mixing, it is a necessary consequence that the Josephson singularities will also be strong. At high frequencies the quasi-particle steps (spaced down from $V = 2\Delta/e$ by intervals of $h\nu/e$) and the Josephson singularities (spaced up from $V=0$ by intervals of $h\nu/2e$) will begin to overlap. This interference gets worse at higher values of LO power. Suppressing the competition from the Josephson effect is the greatest difficulty in achieving high-frequency operation in SIS quasi-particle mixers.

C. Magnetic Fields

The suppression of the dc Josephson effect with magnetic fields was discussed by Josephson [18] and measured by Rowell [19]. The chief difficulty in the present case is achieving adequate suppression for junctions with small area. The junctions used must be kept small in order to minimize the capacitance of the device. Assuming a uniform junction, the requirement for Josephson-effect suppression is that the cross section presented to a magnetic field applied parallel to the plane of the junction

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contains a single quantum of magnetic flux. For a junction length of 1 μm and assuming a penetration depth of approximately 5 10^{-6} cm for Pb-alloys, this cross section is 10^{-9} cm^2. Since the quantum of magnetic flux is 2 10^{-7} Gauss cm^2, this works out to a required field of around 200 Gauss. Although this is smaller than the critical field for destroying the underlying superconductivity, it is large enough to have a significant effect on the size of the superconducting energy gap. Thus, this form of magnetic field suppression is possible for junctions of linear size about 1 μm, but impractical for much smaller junctions.

D. Local-Oscillator Power Requirements

One of the chief advantages of SIS mixers is their small local-oscillator power requirement. Phillips *et al.* [10] estimate an optimum LO level for mixing at 115 GHz of about -50 dBm. Since this power should scale as ν^2, this implies a power requirement of -43 dBm at 250 GHz. This estimate can be understood in terms of Tucker's quantum theory of mixing [13], [14] in which the conversion efficiency depends on the conductances

$$G_{10}=\frac{1}{2}\sum J_n(\alpha)[J_{n-1}(\alpha)+J_{n+1}(\alpha)]\frac{d}{dV_0}I_{DC}\left(V_0+\frac{n\hbar\omega}{e}\right)$$

$$G_{01}=\frac{e}{\hbar\omega}\sum J_n(\alpha)[J_{n-1}(\alpha)-J_{n+1}(\alpha)]I_{DC}\left(V_0+\frac{n\hbar\omega}{e}\right)$$

where $\alpha=eV_1/\hbar\omega$ and V_1 is the LO voltage applied to the junction. These conductances vanish for $\alpha\ll 1$. Thus, values of α of order unity are needed in order to get significant mixing on the first photon step below the gap. This criterion gives a required LO power of the same order as that estimated above. In contrast, competing cooled Schottky-barrier diode mixers in this frequency range [4] require local-oscillator powers many orders-of-magnitude larger (on the order of -10 dBm incident on the diode). Due to the difficulty in getting sufficient LO power in this frequency range, this is a considerable advantage for SIS mixers.

E. Impedance Matching

The impedance matching problem for Schottky-diode mixers is by now fairly well understood. The conventional design for a Schottky mixer mount consists of a section of reduced height waveguide to reduce the RF impedance to about 100 Ω. Then a diode can be selected which reasonably matches both the RF input circuit and a 50-Ω coaxial IF output. Due to the complicated formalism of the theory of quantum mixing, the equivalent problem has not been as well understood for SIS mixers. However, it can be deduced from Tucker's quantum theory of mixing that in the limit of small IF frequencies and small α the IF output conductance is approximately given by

$$G_{00}=\sum J_n^2(\alpha)\frac{d}{dV_0}I_{DC}\left(V_0+\frac{n\hbar\omega}{e}\right)$$

which is simply the slope of the $I-V$ curve near V_0 under conditions of RF voltage bias. The small-signal RF input conductance is similarly related to

$$G_{11}=\frac{e}{2\hbar\omega}\sum J_n^2(\alpha)\left[I_{DC}\left(V_0+\frac{(n+1)\hbar\omega}{e}\right)-I_{DC}\left(V_0+\frac{(n-1)\hbar\omega}{e}\right)\right]$$

which for small values of α is given by the slope of a line joining points on the pumped $I-V$ curve one photon step above and one photon step below the dc bias point. Thus, the impedances presented by the mixer at the RF and IF ports will be different than the normal-state impedance of the junction. In general, the IF impedance will be significantly larger and the RF impedance somewhat smaller. The problem of impedance matching is discussed more completely by Smith and Richards [20] and, with the inclusion of noise considerations, by Wengler and Woody [21]. Optimum performance in the IF is achieved if the mixer output is nearly matched into the IF load impedance. In the RF, optimum conversion efficiency is given by a large source impedance, but best overall noise performance is achieved in a more nearly impedance-matched configuration. The consequence is that in practice it is desirable to have a junction with normal-state impedance of about 50 Ω. The RF driving impedance should be lowered using reduced height waveguide and the IF load impedance should be increased above 50 Ω using a quarter-wave transformer section.

III. Receiver Construction and Performance

The general design of the receiver was based on a scaled-down version of the 115-GHz receiver of Dolan *et al.* [11], the principal departure being the use of circular waveguide. The advantage of circular waveguide at high frequencies is the greater ease in construction and the higher tolerances to which mechanical tuning elements (choked backshorts) can be made. The principal disadvantage is the reduced bandwidth of single-mode operation compared with rectangular waveguide. The waveguide size used in the receiver was 0.97-mm diameter, which allows for single-mode operation to just above the design frequency of 230 GHz. The next higher mode (TM_{01}) has radial electric field lines and is, to first order, decoupled from the currents flowing in the junction.

The junction used was fabricated using photo-lithographic techniques and was similar to the devices described by Dolan *et al.* [11]. The material used was a Pb–In–Au alloy chosen primarily on the basis of its thermal cyclability. The junction cross section is estimated to be about 0.7 μm on a side, giving a device capacitance of about 20 fF. For the device used in these measurements, which had a normal state impedance of 68 Ω, this implies a value of $\omega R_N C\sim 2$ at 230 GHz.

The mixer block, which is shown in Fig. 1, is machined from a single piece of copper and contains an integral IF-line choke. The junction itself is deposited on a 0.1-mm-thick quartz substrate which rests in a groove spanning the waveguide. One end of the junction is attached directly to the mixer block with silver paint while the other end is insulated with a thin sheet of mylar. Behind the junction there is an adjustable backshort which allows for continuous tuning over the atmospheric window from 190 to 300 GHz. The input of the waveguide is attached to a corrugated feed horn. Radiation reaches the feed horn after passing through a 0.025-mm mylar vacuum window and a cooled $\lambda/4$ crystalline quartz filter.

The IF port of the mixer is connected to a cooled two-stage *L*-band GaAs FET amplifier which operates from 1100 to 1650 MHz. This amplifier has a noise temperature of about 12 K averaged over this band and is similar to that described by Weinreb *et al.* [22] except for the omission of a third stage of amplification and the greatly reduced power dissipation (40 mW versus about 200 mW). This latter factor is quite important for operation in a LHe-cooled cryostat.

The normal-state impedance of the junction used in these tests was 68 Ω. No transformers were used to match impedances in either the RF or the IF sections. In the IF the approximately 50-Ω input impedance of the FET amplifier is being driven by the output impedance of the mixer, which is generally considerably

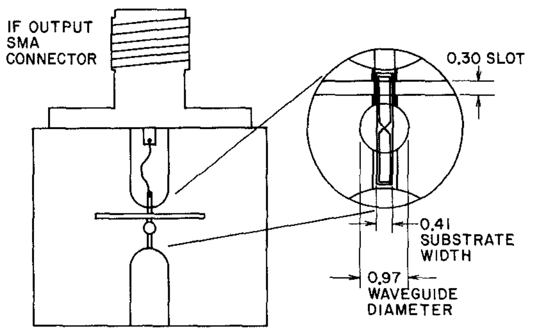

Fig. 1. Diagram of mixer block The view shown is that seen by looking down along the axis of the circular waveguide. The junction is deposited on a 0.1-mm-thick quartz substrate which rests in a vertical slot spanning the waveguide. The metallization covers most of the substrate. The horizontal slot above the waveguide forms the high impedance section of a three-section RF choke on the IF line. All dimensions shown are in millimeters.

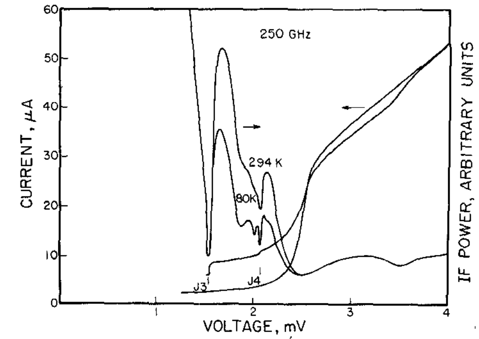

Fig. 2. System performance at 250 GHz. Shown are the unpumped and pumped (~ −43 dBm of LO) $I-V$ curves of the junction as well as the IF power output for room temperature and liquid nitrogen temperature loads. The $I-V$ curves show regions of negative resistance (hysteresis) below about 1.6 mV due to the Josephson effect. The IF power curves show structure at points J3 and J4, where the ac Josephson frequency ($\nu_J = 2eV_0/h$, where V_0 is the dc bias voltage) is an integral multiple of the local-oscillator frequency. Application of a magnetic field suppresses the structure at J3 and J4 as well as showing more clearly a smooth quasi-particle step extending from 1.4 to 2.4 mV.

larger than the junction normal-state impedance. For typical conditions of bias and pumping, this impedance was determined from the pumped $I-V$ curve to be approximately 250 Ω, providing roughly a 5:1 mismatch in the IF. The RF showed a similar mismatch between the 400-Ω waveguide impedance and the mixer input impedance [13], [14]. At high frequencies this was a mostly real impedance somewhat lower in value than the normal-state impedance of 68 Ω. Thus, the RF impedance mismatch is quite considerable, being roughly 8:1. This factor creates quite a significant insertion loss in the receiver. A better situation would be to have transformer sections in either the RF or IF to reduce these mismatches. An IF impedance transformation of a factor of 2 to 4 should be fairly readily achieved without severely limiting the IF bandwidth. A similar transformation in the RF is impossible with the present circular waveguide geometry, although such a transformation could be made using reduced height rectangular waveguide. Finally, the junction impedance could be chosen to better balance out the amounts of mismatch in the RF and IF.

Local oscillator power is provided by a frequency-multiplied klystron. The multiplier consists of a GaAs Schottky diode mounted in a conventional WR-8/WR-3 crossed-waveguide mount [3], [23]. The klystron frequency is doubled to produce frequencies up to 250 GHz and tripled beyond that. For tripled operation the second harmonic was suppressed by using a section of waveguide beyond cutoff. Because of the low power requirements of SIS mixers, this multiplier produces roughly 30 dB more local-oscillator power than is needed at the mixer. As a result, a simple diplexer consisting of a thin (0.025 mm) sheet of mylar can be used to combine the local oscillator and signal beams with only a 1–2-percent insertion loss of the signal.

The performance of the receiver has been measured at a number of frequencies within the design band of 220–250 GHz as well as at several higher frequencies. All measurements were made double-sideband (DSB) and converted to equivalent single-sideband (SSB) performance. Relative sideband response was measured to be balanced to better than 20 percent. The best performance obtained was a receiver noise temperature of 305 K (SSB) at 241 GHz, averaged over the IF band. Measured conversion loss at this frequency was 10.5 dB (SSB). This includes losses due to the impedance mismatches discussed above and losses in the optics, feedhorn, and mixer block. Junction $I-V$ curves with and without applied LO, as well as the responses to hot (294 K) and cold (80 K) loads, are shown in Fig. 2. Application of a magnetic field suppresses the Josephson-effect structure and reveals a smooth quasi-particle step without greatly affecting the sensitivity of the receiver.

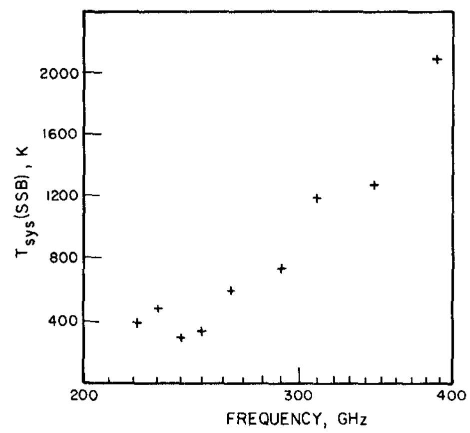

Fig. 3. Single-sideband receiver noise temperature as a function of frequency. The measurements at frequencies above 260 GHz were made at a time when the receiver performance at the lower frequencies was about 35-percent worse than shown here. Hence the upper portion of the curve may be unduly pessimistic.

Tuning to other frequencies can be accomplished by tuning the mixer backshort position as well as the backshorts on the multiplier. Generally it is also necessary to optimize the amount of local-oscillator power and the voltage bias on the junction. The local-oscillator power level is not critical, but the bias voltage is moderately critical due to the complex Josephson-effect structure. A plot of system noise temperature versus frequency is given in Fig. 3. All measurements shown were taken at 4.2 K and without any applied magnetic field. The receiver performance is broadly optimized over a band from 200 to 300 GHz.

Included in Fig. 3 are measurements made at frequencies much greater than the nominal band of the receiver. At these frequencies the mixer block size and geometry are not optimized, but nevertheless such measurements serve to test the principles for operating SIS mixers at higher frequencies. In addition, the mode of operation changes significantly due to increased competition from Josephson-effect mixing, a problem which is just beginning to be severe at 230 GHz. At the higher frequencies it is helpful to use a combination of lower temperature operation (2.2 K) to increase the superconducting gap and applied magnetic fields to suppress the Josephson effect in order to achieve a stable mode of mixing. The highest frequency at which tests have been made so far is 388 GHz where a noise temperature of 2100 K SSB was measured. Experience indicates that with a mixer block suitably optimized for this frequency, a noise temperature of ~600 K SSB should be readily achieved.

IV. Summary

An SIS quasi-particle mixer–receiver has been constructed for use at frequencies around 230 GHz. Its performance is comparable with or better than that of the best competing cooled Schottky-diode mixers in this frequency range. Furthermore, it has the significant advantage of a low local-oscillator power requirement. This greatly relaxes the constraint of highly efficient frequency-multipliers to supply the LO, as well as relaxing the requirements of the diplexer for combining the signal and LO.

In its present configuration, the receiver suffers from severe impedance mismatches in both the RF and the IF. These mismatches are the chief factors limiting receiver performance. An improved receiver incorporating impedance-matching transformers should show at least a factor of 2 better noise temperature.

Tests have also been made of performance at higher frequencies. It seems likely that good receiver noise temperatures can be achieved out to frequencies around 500 GHz. Further increases in frequency are difficult because of competition from the Josephson effect, but some useful performance may be possible out to 1000 GHz.

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Design Parameters of Inhomogeneous Asymmetrical Coupled Transmission Lines

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***Abstract*—The parameters of asymmetric coupled lines in an inhomogeneous medium (mode numbers and mode impedances) are derived in terms of self and mutual static capacitances of the system in the filled and empty structures. These capacitances are computed by using the network analog method. The effect of dispersion is accounted for by introducing an approximate dispersion model. A set of design curves for different geometric configurations are presented which can help in the design of couplers and filters. The obtained numerical results, taking into consideration the dispersion effect, were found to be in a good agreement with the only available published data.**

I. Introduction

Coupled line structures are utilized extensively as building-blocks for filters, directional couplers, impedance transformers, and other important transmission-line parameters. The main difference between the performance of asymmetric and symmetric coupled lines is that the former provide impedance transformation besides the conventional coupling. This should prove to be useful in many practical applications such as matching of a monitor diode detector to a main line. However, there is still considerable lack of their design data and its frequency dependence. The exact knowledge of these data is necessary to utilize the added flexibility offered by the asymmetric microstrip configurations especially in filters and couplers. In the literature, only the analysis of asymmetric coupled lines is dealt with [1]–[5]. In

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