# Millimeter Wave Superconducting Receivers

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**Abstract**

We review the recent work done at Berkeley on the development of millimeter wave heterodyne mixers using superconductor-insulator-superconductor (SIS) junctions. Two types of mixers have been developed: a conventional waveguide system using a resonant cavity and a open-structure quasioptical system using planar antennas and lenses. Using the waveguide system, we have achieved the lowest mixer noise level yet achieved (within 25% of the quantum limit) at 95 GHz. The quasioptical system has achieved a good mixer performance up to 200 GHz, and it has shown great promise to be used at submillimeter wavelengths.

## I. Introduction

The beautiful phenomena of superconducting tunneling were discovered about 30 years ago. Shortly thereafter, interest developed in the use of these effects for the detection and mixing of infrared and millimeter wave radiation. The first attempts made use of Josephson pair tunneling, which achieved limited success.[1] A true success came after the invention of SIS (superconductor-insulator-superconductor) mixers which utilize the nonlinear quasiparticle current-voltage characteristics to achieve efficient mixing. The first SIS quasiparticle mixer made had lower noise than the best Josephson mixers ever made.[2] Within two years of its invention, the SIS mixer was in active use on a radio telescope.[3] These SIS quasiparticle mixers are used in the lowest noise receivers from ~60 to 600 GHz. The major applications are in molecular line radio astronomy and measurements of the anisotropy of the cosmic microwave background.[4]

The quantum theory of mixing developed by Tucker[5] to explain the properties of the super Schottky diode gave a complete theoretical treatment of the SIS quasiparticle mixer and also the direct detector. Two novel phenomena were predicted by the quantum theory: A quantum mixer can achieve a mixer gain, that is, a mixer conversion efficiency greater than unity. Also, a quantum mixer can have a mixer noise temperature $T_m$ as low as allowed by the Heisenberg's uncertainty principle, which is $\hbar\omega/2k$. Both predictions were verified experimentally by several groups.

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A comprehensive review of the field of SIS receivers has been published recently.[6] In this paper we will only review the work done at Berkeley on the development of SIS mixers: a waveguide SIS mixer which has achieved the quantum-limited noise performance, and a quasioptical SIS mixer which has potential for use at submillimeter wavelengths.

## II. Quantum-limited waveguide SIS mixers at 100 GHz

The theory of quantum detection shows that any narrow-bandwidth phase-preserving linear amplifier must add noise of spectral density referred to the input of[7]

$$S_N \geq |1 - G_p^{-1}|\, \hbar\omega/2\,, \qquad (1)$$

where $G_p$ is the photon number gain, and $\omega$ is the angular frequency of the signal. An SIS mixer operated in the weak signal limit is linear, preserves phase, and amplifies photon number. Therefore, the above quantum limit applies. Since an SIS mixer almost always operates in the regime of large photon number gain, the quantum limit (1) reduces to $S_N \geq \hbar\omega/2$.

This quantum noise is very small in units of temperature, it is 1 K at 40 GHz and it scales linearly with the frequency. Therefore, it is a great challenge to achieve a quantum-limited mixer performance at millimeter-wave frequencies. Several requirements must be satisfied to meet this challenge: a well-designed and well-constructed RF system that has minimum RF signal losses, and a high-quality SIS junction with a sharp nonlinear I-V characteristic and a low leakage current below the gap voltage.

The RF system used in this work was constructed by Räisänen et al.[8]. It contains two variable temperature blackbody sources, one for RF and one for IF, to calibrate the noise performance of both the SIS mixer and the whole system. The mixer block is a quarter-height W-band (75-110 GHz) waveguide with an adjustable noncontacting backshort, which is the only mechanical tuning element.

The SIS junctions used in this work are $Ta/Ta_2O_5/PbBi$ tunnel junctions fabricated at Yale University.[9] The I-V characteristics of the junctions show an extremely sharp nonlinearity at the gap voltage, as shown in Fig. 1(a). The voltage width $\Delta V$ over which the sum-gap current step rises from 0.1 to 0.9 of its full value is less than 0.01 mV. The leakage current at 0.8 $V_{gap}$ is less than 0.05 $I_c$.

We have made accurate measurements of the mixer noise over the entire W-band. The result is shown in Fig. 2. The mixer noise is expressed in units of quanta. In these units the quantum noise limit is 0.5, which is shown as a horizontal line in the figure. Our minimum mixer noise is a maximum of 0.11±0.31 quanta above the quantum limit for a phase-

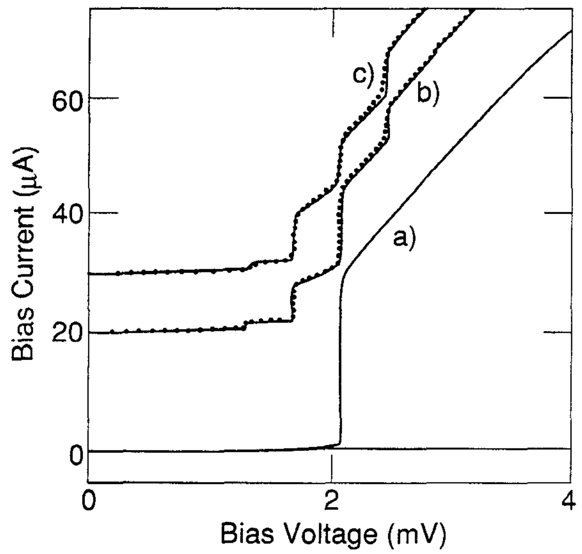


Figure 1. (a) Measured dc I-V curve of the $Ta/Ta_2O_5/PbBi$ junction studied at 1.3 K. (b) and (c) Experimental and calculated pumped I-V curves. The solid line is the curve calculated from (a), the dots are experimental data.

preserving linear amplifier. This is, to our knowledge, the closest approach to the quantum limit measured in any mixer. We have also compared the experimental results with the predictions from the quantum theory of mixers. The agreement is very good.[9]

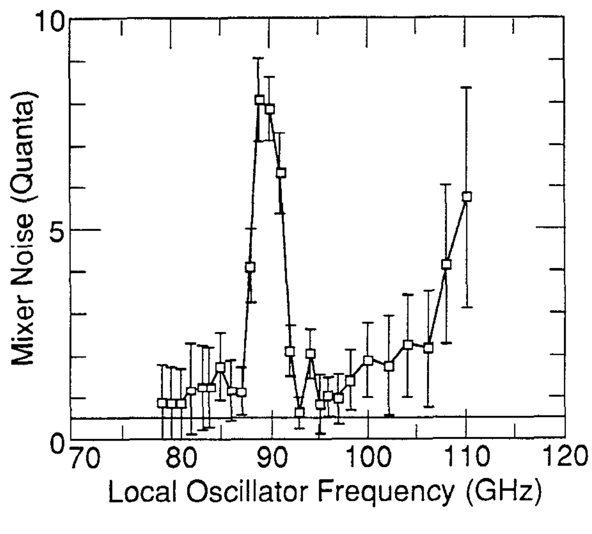


Figure 2. Added mixer noise as a function of frequency. The horizontal line at 1/2 is quantum limit imposed by the uncertainty principle.

## III. Millimeter-wave quasioptical mixers

Thin-film SIS tunnel junctions are compatible with other lithographed superconducting receiver components such as planar antennas, transmission lines, and filters. It is therefore attractive to use optical lithography to make integrated planar quasioptical receivers at high frequencies so as to avoid the fabrication problems associated with waveguide structures. One of the major problems encountered at these high frequencies is the capacitive roll-off, which can significantly decrease the RF coupling efficiency of the mixer. In a waveguide mixer, this capacitance can be tuned out by the backshort or other mechanical adjustment. In quasioptical mixers, we must either fabricate high current density, small area (<<1 $\mu m^2$) junctions so that the capacitance does not dominate the RF coupling, or use a lithographed inductive element to resonate the capacitance at the signal frequency. The first approach requires difficult microfabrication techniques that are not widely available. The use of an inductive tuning element relaxes the requirement on junction size and current density.

The $Nb/NbO_x/Pb$-In-Au junctions used in this study are limited by fabrication techniques to a $1.7\times1.7\ \mu m^2$ area, so that capacitive roll-off is a serious problem for frequencies at and above W-band. We have used two types of integrated tuning elements in our quasioptical SIS receiver. One is an inductive wire in parallel with a 5-junction array; the other is a microstrip stub with an inductive admittance at the desired frequency. Schematic diagrams of these tuning structures are shown in Fig. 3. These structures have been used on planar quasioptical mixers at frequencies from 90 to 360 GHz. Since conventional microwave test apparatus is not available at such high frequencies, special techniques are used to evaluate the RF coupling provided by such structures. These have included using a Fourier transform far-infrared spectrometer as a sweeper and the mixer junction as direct detector.[10]

Since planar antennas located on a dielectric surface radiate primarily into the dielectric, the RF signals are introduced through the back surface of the dielectric, which is curved to form a lens to avoid surface waves. Our early work on planar integrated SIS mixers began with bow-tie antennas,[11] but attention has shifted to log-periodic antennas which have antenna patterns with more symmetrical central lobes[12] and so can couple more efficiently to telescopes.

Our best mixer performance in W-band is obtained from a five-junction array with an inductive wire. The lowest mixer noise temperature is 115 K at 87 GHz, and the coupled mixer gain is -3.4 dB. The FWHM bandwidth of the coupled mixer gain is 8 GHz. We have also tested mixers with a single junction and an open-ended microstrip stub which is $3\lambda/8$ at the fundamental frequency. The impedance of the stub is inductive to resonate the junction capacitance at frequencies close to harmonics of the fundamental frequency. The mixer performance is quite good up to 200 GHz. Figure 4 shows a pumped I-V curve for a single junction with a stub designed for 180 GHz. Figure 4 also shows the IF power as a function of dc bias voltage for a hot (300 K) and a cold (77 K) RF load placed in front of the mixer. From the difference of the two IF power curves, we deduce the lowest mixer noise temperature is 200 K at 176 GHz and the receiver noise temperature is 250 K. The best coupled gain of -4.5 dB occurs at the same frequency. The FWHM bandwidth of the coupled gain is about 3 GHz. Table 1 summarizes the best performance of our quasioptical SIS mixers.[13]

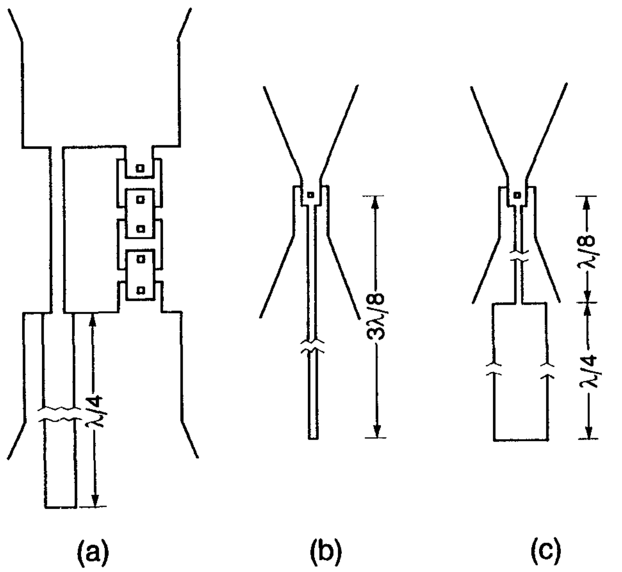


Figure 3. Layout of window junctions and lithographed RF matching structures used in quasioptical SIS mixers from 90 to 270 GHz. (a) Series array of five junctions with a parallel wire inductor terminated in an open-ended λ/4 microstrip stub. (b) Single junction with an inductive open-ended 3λ/8 stub. (c) Single junction with an inductive λ/8 stub whose end is RF short-circuited by an open-ended λ/4 stub. This configuration has twice the bandwidth of (b).

Table 1

| Frequency range | 90 GHz | 180 GHz | 270 GHz |
|---|---|---|---|
| 5-junction array with tuning wire | $T_m$ = 115 K<br>$G_c$ = -3.4 dB<br>Δf = 10 GHz | ----------- | ----------- |
| Single junction with stub | $T_m$ = 150 K<br>$G_c$ = -4.8 dB<br>Δf = 5 GHz | $T_m$ = 200 K<br>$G_c$ = -4.4 dB<br>Δf = 3 GHz | $T_m$ > 2000 K<br>-------------- |

Table 1. The best mixer performance of quasioptical SIS mixers with integrated tuning elements and log-periodic antennas.

As indicated in Table 1, the mixer performance is very poor at frequencies above 270 GHz, even though the coupled RF power deduced from the pumped I-V curves indicates there are resonances at the designed frequencies. One possible explanation is that losses in the stub, due both to the surface impedance of the superconducting films and to the insulating layers, become significant at these high frequencies. A CalTech group has achieved an excellent mixer performance over an extremely broad bandwidth from 100 to 760 GHz by using high current density, submicron SIS junctions.[14] The capacitive roll-off is not significant for these junctions so no tuning elements are needed and used.

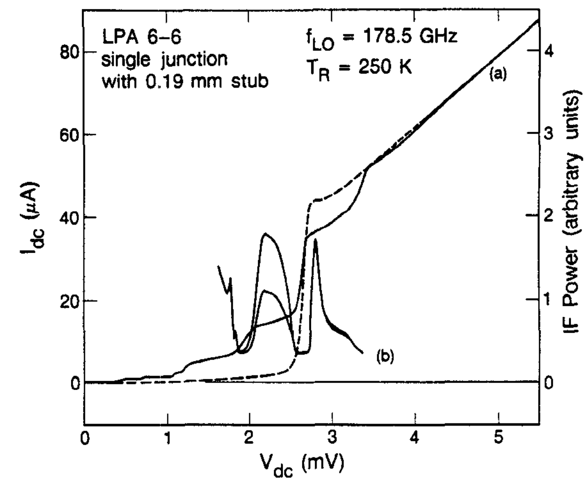


Figure 4. Response data for a quasioptical mixer. (a) I-V curves of a pumped (solid line) and unpumped (dashed line) junction. (b) IF power as a function of dc bias voltage. The top curve is for the hot (300 K) and the bottom curve is for the cold (77 K) load.

## Conclusion

We have achieved the quantum-limited mixer performance at W-band frequencies using conventional waveguide SIS mixers. The comparison between the measured mixer gains and mixer noise temperatures and the predictions from Tucker's quantum mixer theory is very good. We have also achieved good mixer performance up to 200 GHz using a quasioptical open-structure system. Using high current density and submicron SIS junctions, the quasioptical SIS mixers have the potential to be used at submillimeter wavelengths.


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