HIGH GAIN AND NOISE IN SIS MIXERS AT SUBMILLIMETER WAVELENGTHS

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Abstract

Superconducting tunnel diode (SIS) mixers are used for radio astronomy from 100 to 500 GHz. They are being considered for NASA spaceborne astronomy at frequencies near 1,000 GHz. We report measurements of gain and noise in SIS mixers at 230 and 492 GHz. We measure high gain and noise associated with Josephson currents which have not been previously reported. These measurements show that Josephson currents are increasingly important as operating frequencies are raised.

We discuss the techniques we use to make these measurements. Measurements made with hot and cold blackbodies are shown to be inaccurate at high frequencies. The problem is that SIS's do not always respond linearly to the signal power incident on them. This is particularly important when 1) very broad band mixers are used and 2) Josephson effect currents are important. Both of these circumstances are present in the quasioptical SIS mixers favored for 500 GHz and higher. We use monochromatic signals to measure gain and noise to get around these problems.

Introduction

Mixers using superconducting tunnel diodes called SIS's (Superconductor-Insulator-Superconductor) as their detector are the most sensitive available for millimeter spectroscopy. They are the front end of choice for millimeter radio astronomy [1-5]. SIS's are predicted to work well at submillimeter wavelengths [6], and are now in astronomical use at 492 GHz [7]. Excellent reviews of the field are available [8, 9].

There are two charge carriers in the SIS: 1) superconducting or Cooper pairs of electrons and 2) quasiparticles or single electrons. The SIS can be thought of as a pair-device and a quasiparticle-device connected in parallel. The pair-device is a Josephson junction which has a non-linearity in its IV at 0 V. The quasiparticle-device has an IV similar to the forward conduction IV of a regular diode. It has a non-linearity in its IV at its gap voltage, V_{GAP}. We are working with lead alloy SIS junctions. The dc current-voltage curve (IV) for our junction can be seen in both fig. 1 and fig. 2. The pair and quasiparticle non-linearities are both present. 1) The portion of the IV labeled S_0 is a non-zero current at 0 mV due to the pair-device. It can be seen to disappear when a magnetic field is applied to the SIS. 2) There is a sudden rise in current at V_{GAP} = 2 mV due to the quasiparticle device. This is only slightly affected by the presence of the magnetic field.

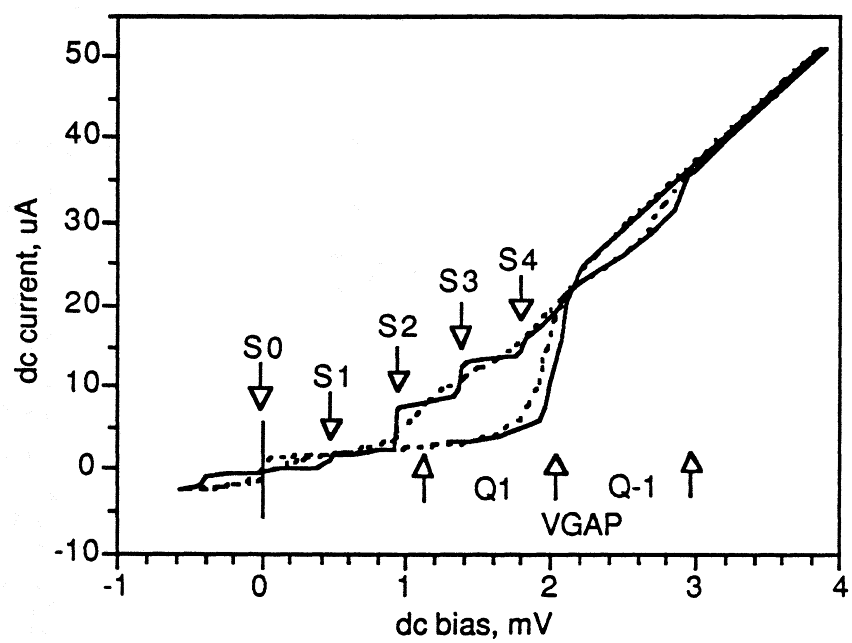

Fig. 1) SIS IV curves with and without 230 GHz radiation applied. The dashed lines are with magnetic field applied to suppress the Josephson effect, the solid are without. Shapiro step voltages and quasiparticle photon steps are shown.

Both the pair and the quasiparticle devices respond to incident radiation. In fact, both devices are so sensitive that they respond in a quantum fashion to radiation at frequencies as low as 100 GHz (even lower for SIS's fabricated from other materials). The SIS IV with 230 GHz radiation is shown in fig. 1. The structures in the IV labeled S_n are the Shapiro steps due to mixing of the incident radiation with Josephson currents in the pair-device. They are labeled sequentially as they appear above the Josephson nonlinearity at 0 V. They are spaced in voltage by hf/2e, the energy of a photon divided by the charge of a carrier in the Josephson junction. The quasiparticle device has steps in its response as well. They are labeled Q_n and are labeled sequentially away from the quasiparticle non-linearity at V_{GAP}. Q_1 is only clearly seen when the magnetic field is applied to suppress S_2, S_3, and S_4. Their spacing in voltage is hf/e, twice as large as Shapiro step spacing because the quasiparticle carrier charge is only half as much as a pair.

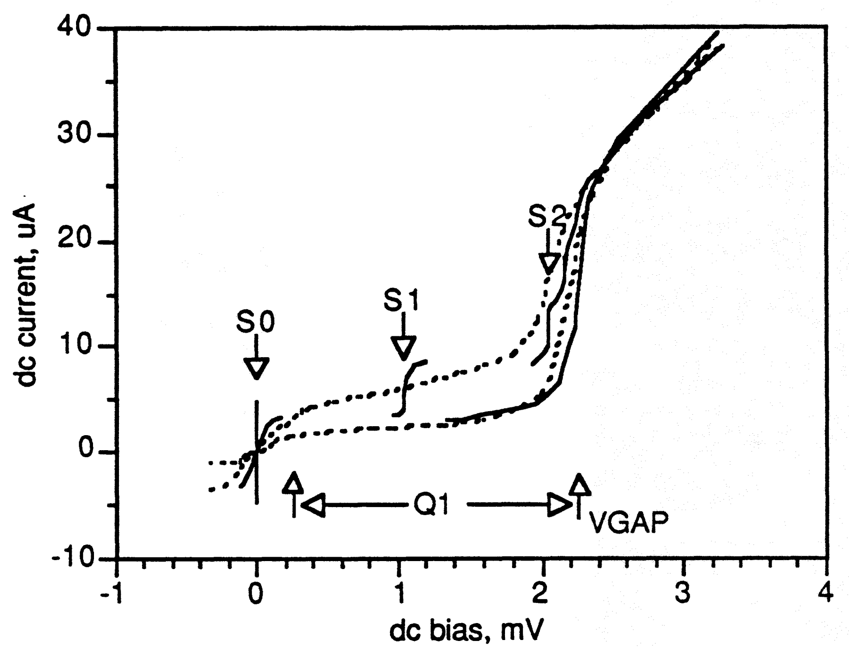

Fig. 2) SIS IV curves with and without 492 GHz radiation. The dashed lines are with a magnetic field applied, solid lines are without. Broad ranges of dc bias are not possible unless a magnetic field applied.

At 492 GHz, the quasiparticle steps are spaced 2 mV apart, and the Josephson step separation is 1 mV. An IV for an SIS at 4.2 K is shown in fig. 2. At this high frequency, there is only one quasiparticle step below the gap, and only two Shapiro steps. Without magnetic field applied, the SIS cannot be stably biased over most of the range from 0 to 2 mV. The SIS switches hysteretically between S_0, S_1, and S_2 in this range. This has very important implications for an SIS mixer at 492 GHz. At many frequencies, best SIS mixing performance occurs for a dc bias on Q_1 at about 1.9 mV. In fig. 1 it can be seen that stable bias is possible at this and all other dc bias voltages whether or not the pair currents are suppressed by magnetic field. But at 492 GHz and (we presume) higher frequencies, it is only possible to have stable dc bias points on Q_1 if magnetic field suppresses pair currents. Just from the IV curves, we can see the increased importance of pair currents as frequency of SIS mixer operation is increased!

Quasioptical SIS Mixer

For work comparing SIS mixer performance over a broad range of millimeter and submillimeter wavelengths we require a radiation coupling structure which works over a very broad range. The mixer we use is identical to the quasioptical SIS mixer used at the Caltech Submillimeter Observatory [7]. The SIS is coupled to a planar spiral antenna, which is placed on the back of a quartz hyperhemispherical lens. This structure is similar to the original bowtie SIS mixer [10]. Both of these are coupled to radiation over a large spectral range including 100 to 500 GHz. Thus, we can measure a single junction's response to a broad range of frequencies.

The receiver at Caltech has been operated at 492 GHz with receiver noise temperatures below 1,500 K. Our receiver is about ten times as noisy. Much of this inferiority may be due to our use of lower current density SIS's. In this case, we are losing proportionally more of our signal due to SIS capacitance than the Caltech workers. Even though our receiver is noisier, we believe the effects we report here are relevant to the performance of lower noise receivers.

Gain and Noise Measurements

Hot and cold loads (blackbodies at 295 and 77 K) are usually used to calibrate astronomical receivers. The load provides a signal power of $S_{RF} = k_B T_L B$ where k_B is Boltzmann's constant, T_L is the temperature of the blackbody, and B is the bandwidth in which the power is measured. B is defined by a bandpass filter in the IF circuit. The total IF power measured includes both signal and noise,

$$P_{IF}(T_L) = S_{IF}(T_L) + N_{IF}.$$

The signal and noise portions of this are

$$S_{IF}(T_L) = GS_{RF} \quad \text{and} \quad N_{IF} = Gk_B T_N B.$$

G is the conversion gain of the mixer, T_N is its noise temperature. The mixer has a signal to noise ratio SNR = 1 if $T_L = T_N$.

Two major difficulties arise in the measurement of some receivers using hot and cold loads. First, the accuracy in the determination of T_N is bad when T_N is larger than a few thousand degrees. Second, a change in P_{IF} as T_L is changed is not necessarily due to linear mixing. SIS diodes with Josephson currents in them are sensitive to very small power levels. This non-linear response to incident signal power is particularly severe when an SIS is dc biased near a Shapiro step. Submillimeter SIS mixers seem always to be biased between very strong Shapiro steps, so this non-linear response is a particular problem for high frequency SIS mixers.

The non-linear response of SIS mixers to hot and cold load radiation seems generally to increase P_{IF} as T_L is raised. In the normal way of finding G and T_N from measurements with two values of T_L, this produces an overestimate of G and an underestimate of T_N. In extreme cases, values of T_N below zero have been calculated.

The problem of using blackbodies as calibration signals is that they are incoherent. There is no way to distinguish at the mixer output what portion of P_{IF} is due to down-conversion of S_{RF}, and what portion is due to mixer noise. We can get around this problem by using monochromatic or coherent signals. In this case, a spectrum analyzer at the IF frequency is used to find S_{IF} and N_{IF}. The down-converted coherent signal, S_{IF}, appears as a spike well above the noise background. N_{IF} is just the height of the noise background. P_{IF} is now made up of two clearly distinguishable components, a spike which is signal and a smooth, broadband background which is noise.

Unfortunately, it is difficult to know accurately the power coupled from a coherent source into a mixer. First, it is not easy to make accurate power measurements of monochromatic millimeter and submillimeter signals, especially signals of low enough power to be useful in heterodyne measurements. More importantly, it is difficult to focus and align optics between the coherent source and the mixer so that nearly 100% of the signal power is coupled into the mixer. Blackbody loads do not have this problem as they can be made much bigger than necessary. But the coherent source radiates into only a single mode of the radiation field which must be made to overlap with the radiation mode to which the mixer responds.

As a result, we make measurements assuming that our signal oscillator power is unknown, but constant in time. In this case, we cannot make an absolute measurement of gain or noise temperature, but we can make relative measurements. In particular, we can say how gain or noise changes as things are varied: LO power level, dc bias voltage, magnetic field strength, & c.

All of the relative measurements of gain and noise can be made absolute if even one good hot and cold load measurement of noise temperature can be made. Perhaps we have reason to believe we do not see non-linear response to hot and cold load in mixers operated with high LO power and biased near the gap voltage. Then measurement of gain and noise with hot and cold loads under this condition give an absolute calibration to all relative measurements made, even to relative measurements made under bias conditions in which it is known that the mixer responds in a non-linear way to hot and cold loads.

Two Oscillators

The simplest and most versatile set up to measure gain and noise of a mixer with a coherent signal is to use two rf oscillators, one to act as LO and one to serve as the signal. The signal oscillator must supply orders of magnitude less power to the mixer than the LO does. A major problem of the two oscillator system of gain measurement is the expense of submillimeter oscillators. On the other hand, astronomical groups will often keep two oscillator systems around for reliability. Also, sources which have insufficient power output to serve as LO's can still be used as signals.

Sidebands

A cheaper way to produce coherent signals is to weakly modulate the LO source at the IF frequency. The radiation leaving the oscillator will now have low power sidebands spaced an IF frequency away from the LO. It will now carry small signals at the signal and image frequencies. This modulation is straightforward with almost any millimeter or submillimeter source. A standard submillimeter oscillator is a 100 GHz Gunn diode oscillator driving a Schottky diode multiplier. The Schottky diode will usually have a coaxial connection for its dc bias. We use a coaxial-T and a dc block to couple a 1.5 GHz signal into the Schottky diode along with its dc bias. In the simplest picture, we are modulating the bias on the multiplier, and therefore modulating its efficiency. The resulting LO leaving the oscillator is amplitude-modulated, and thus has sidebands at the signal and image frequencies of the mixer. Their intensity with respect to the LO can be controlled by varying the amplitude of the 1.5 GHz diode modulation.

We assume that virtually any LO source can be made to produce sidebands. In particular, a Gunn or YiG oscillator could have a 1.5 GHz signal superimposed on its dc bias. A Klystron could have its reflector voltage modulated by 1.5 GHz.

Receiver Gain with Coherent Signals

Measurements at 492 GHz have been made using both the two oscillator method and the sideband method. Measurements at 230 GHz have been made using the sideband method and hot and cold loads (we did not have access to two independent oscillators at this frequency).

One measurement that can be made with two oscillators that cannot be made with the sideband method is mixer gain as a function of LO power. With the sideband method, changing the LO power also changes the signal power, so different IF power out of the mixer is no longer simple to interpret as a mixer gain change. However, if the LO and its carriers were passed through a calibrated attenuator, the change in signal powers would be known as the LO power was varied, and it would be possible to learn how gain varies with LO power.

Gain at 492 GHz

We show gain measurements of our 492 GHz mixer as LO power is varied in fig. 3. The measurements on S_0 and S_2 are made with no magnetic field applied to the SIS. The gain measured on Q_1 corresponds to the usual way an SIS is used as a mixer at millimeter wavelengths. A magnetic field is applied to suppress Josephson currents for the measurement of gain on Q_1. Interestingly, if the magnetic field is turned off we see that a dc bias on two of the Shapiro steps has a gain which is over twice as high as mixing on the quasiparticle step. We see that gain on S_0 is a sharply peaked function of LO power, while mixing on S_2 and Q_1 have very similar dependences on LO power. We suspect that this similarity is because mixing on S_2 comes from a complicated interaction between quasiparticle and pair current mechanisms.

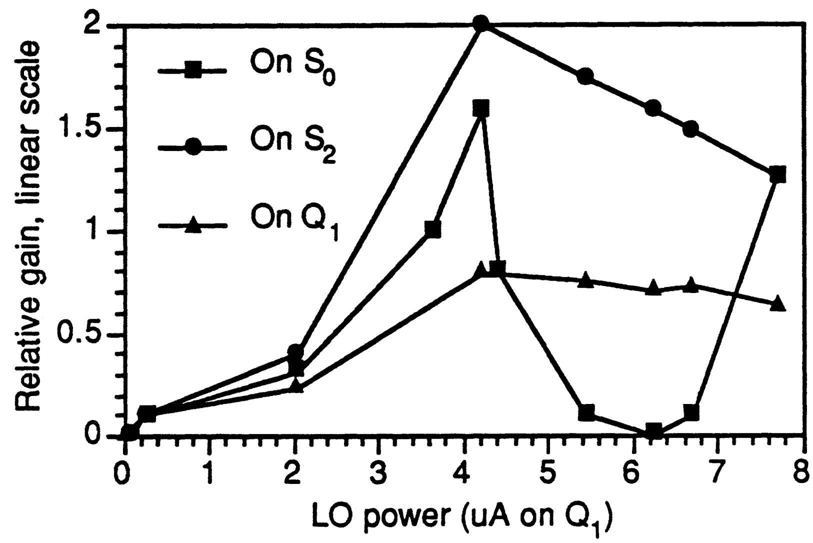

Figure 3) Relative gain at 492 GHz is measured as LO power is increased. Two of these curves are for bias points at the gain maxima near S_0 and S_2, with no magnetic field. The third is at the gain maximum of Q_1 with magnetic field.

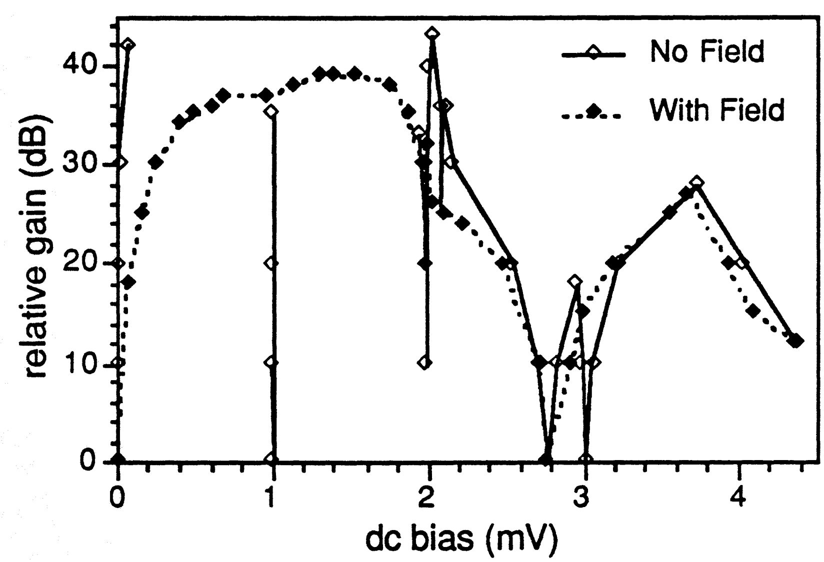

Figure 4) Relative gain at 492 GHz with and without magnetic field applied to suppress Josephson effects.

Fig. 4 shows relative gain at 492 GHz as a function of dc bias voltage. LO power for the No Field case is set to maximize the gain peak at 2 mV (on S_2). The LO power for the With Field case is set to maximize gain at 1.6 mV. Relative gain is now shown on a logarithmic scale; great dynamic range is possible in gain measurements with coherent signals. The broad gain peak between 0 and 2 mV measured with magnetic field present shows that relatively high gain can be found nearly everywhere on Q_1, the broad quasiparticle photon step. With no field, we again see that higher gain is available on S_0 and S_2 then on Q_1. We also see that gain on the Shapiro steps is zero at their low dc voltage end, and the gain maximum occurs at their high dc voltage end. It is not easy to see in fig. 2, but the Shapiro steps actually have a finite slope. This may be an artifact of our bias circuit. It may be more correct to say that the Shapiro step gain is zero at its low current end and high at its high current end.

Sideband Coherence: No Effect on Gain

The sideband method generates both an upper and a lower sideband. However, these are not independent signals, they are phase referenced to the carrier and each other by virtue of arising from an amplitude modulation of that carrier. There are mixing processes such as parametric amplification which may actually rely on a phase modulation of the LO by the signal. Our sideband system might drastically underestimate the gain in such systems.

We checked the validity of the sideband technique against the two oscillator technique at 492 GHz. We did this by simultaneously modulating the LO at 1.5 GHz, and running the second signal oscillator at slightly more than 1.5 GHz above the LO frequency. We looked at the IF on a spectrum analyzer and could see both signals side by side. We then varied dc bias voltage and watched the IF power of both techniques. Relative gain measured both ways was identical. This was particularly important on the high gain Shapiro steps which we thought might be doing some parametric mixing, and would therefore show a lower relative gain when measured by sidebands. They didn't, so we see no evidence that gain due to the Josephson effect is parametric.

Gain at 230 GHz

Fig. 5 shows the gain of our SIS mixer at 230 GHz as a function of dc bias voltage. This was measured using the sideband method. Without field applied, dc biases between S_0, S_1, S_2, and S_3 showed gain which was visibly fluctuating on the spectrum analyzer. We assume that the SIS IV is actually slightly hysteretic between these steps. This hysteresis is masked in fig. 1

because our dc bias circuit uses feedback to achieve a constant voltage bias. We show gain with no field only where we found it to be stable. With magnetic field applied, all dc bias points show stable gain.

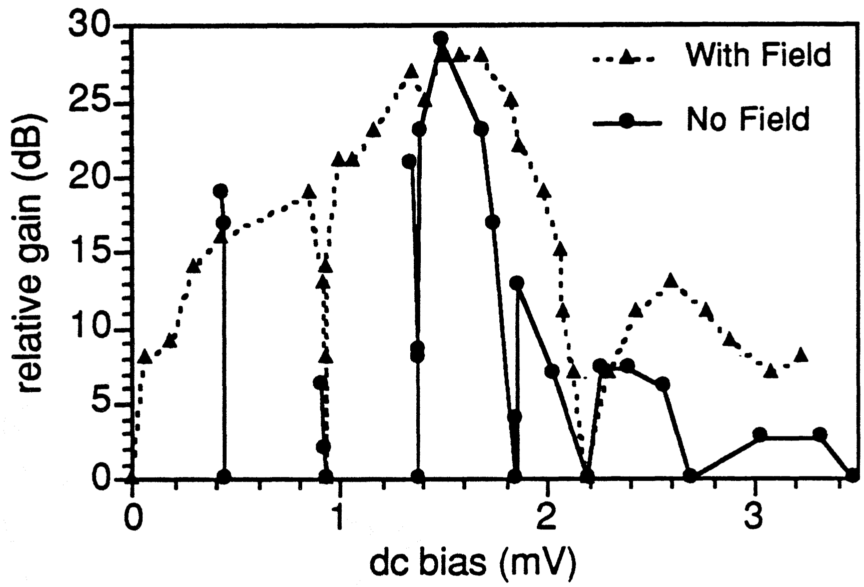

Figure 5) Relative gain at 230 GHz, with and without magnetic field to suppress Josephson effect.

The higher mixer gain is found with no field applied, as it was at 492 GHz. However, the gain is only about 1 dB higher than with field, and it is not occurring on a Shapiro step, but rather between them. We believe that mixing at this point is not influenced by pair currents. We believe the gain is a little higher without field applied because the underlying quasiparticle IV is a little bit better quality when no magnetic field is applied, as can be seen in fig. 1.

When magnetic field is applied, we might hope to see clear differences between the gain on Q_1 and Q_2. We do see higher gain in the region of Q_1 then in the region of Q_2. However, our magnetic field does not completely suppress Josephson currents. As a result, the shape of the gain curve shows deep minima at S_2 and S_5 which make it harder to distinguish clearly the quasiparticle step.

Gain Calculated From Current Responsivity

Information about SIS mixer gain can be gotten from measurements of the dc IV at two slightly different LO power levels. This is explained by the Amplitude Modulation model of SIS mixer gain [11]. The current responsivity of a detector is

$$R_I(V,P_{LO}) \approx \frac{I(V,\, P_{LO}+dP_{LO}) - I(V,\, P_{LO})}{dP_{LO}}$$

where I is the dc current through the detector, V is the dc bias voltage, and dP_{LO} is a small change in the applied LO power. A relative responsivity can be calculated numerically from two IV curves taken at slightly different LO powers without knowledge of absolute power levels.

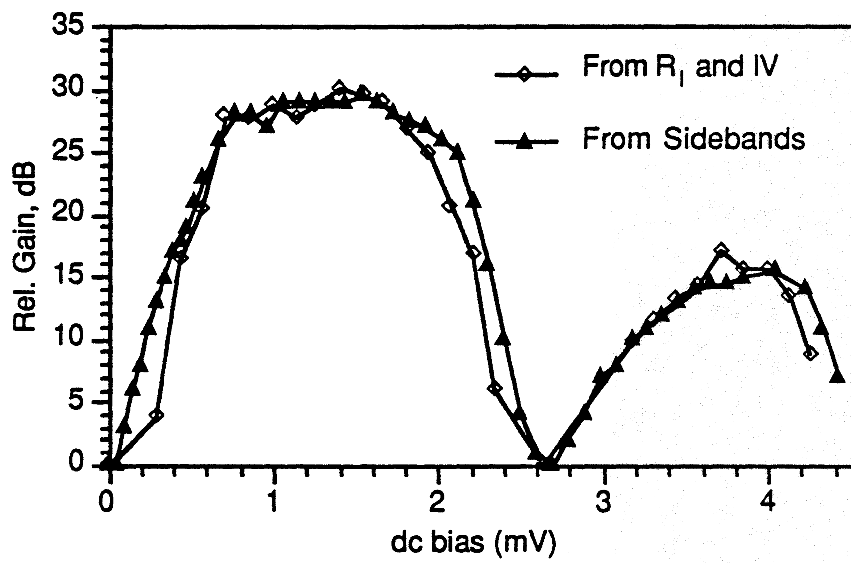

Figure 6) Relative gain at 492 GHz, measured with sidebands and calculated from IV curve measurements.

The total rf power P_{RF} incident on the SIS when illuminated by a signal P_S and P_{LO} is

$$P_{RF}(t) = P_{LO} + P_S + \sqrt{2P_{LO}P_S}\cos\omega_{IF}t.$$

The time varying part of this power causes a time varying current which is coupled into the following IF amplifier as IF power. Taking into account the output admittance G_D of the SIS mixer, the mixer's available gain is

$$G_A = R_I^2 P_{LO}/G_D.$$

In fig. 6, available gain from this expression is plotted along with gain measured using the sideband method. An arbitrary scaling factor is used to make the two relative gain curves overlap. The agreement is quite good over the whole range of bias voltage and gain magnitude. We have made these measurements with Josephson currents suppressed, but we see some preliminary evidence that the high gain on Shapiro steps can also be explained in terms of an Amplitude Modulation model.

Noise Measurements with Coherent Signals

Relative gain measurements are really just a measure of mixer IF output power for a constant but unknown input signal. Of primary importance with SIS receivers for astronomy is signal to noise ratio (SNR). As with gain, we wish to know how this varies with changing LO, dc bias voltage, etc. Again, as with gain, a relative measure of SNR will yield valuable information.

If we use a very broad filter in the IF, we can measure mixer noise power N_{IF} with the input signal turned off. This is a more accurate way of measuring the noise floor surrounding the signal on a spectrum analyzer, as discussed above. S_{IF} is the IF power measured in a narrow band filter with the coherent signal turned on. Then the signal to noise ratio of the mixer is SNR = S_{IF}/N_{IF}. This SNR will be proportional to the inverse of the mixer noise temperature, SNR $\propto T_N^{-1}$.

SNR at 230 GHz

In fig. 7, we show the SNR calculated from coherent signal measurements at 230 GHz. Even though the maximum gain with and without the magnetic field applied are nearly the same (fig. 5), the SNR of the mixer is about 40% better when no field is applied. However, this SNR is sharply peaked as plotted against dc bias voltage. In fig. 1, it can be seen that the IV with no LO applied is somewhat degraded by the presence of magnetic field. It may be that this accounts for the better noise performance of the SIS here without field applied.

SNR at 492 GHz

Figure 8 shows the SNR measured at 492 GHz with and without magnetic field. Here we see the surprising fact that the high gain of the mixer on the Shapiro steps is not associated with a high SNR. In fact, the SNR on the broad quasiparticle step Q_1 is about twice as high as the SNR at the top of S_2, even though its gain is only half as high!

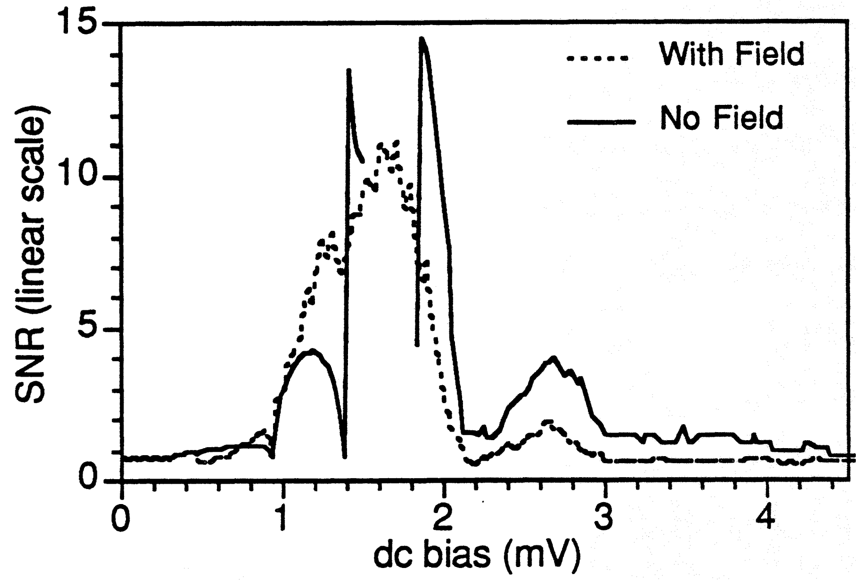

Figure 7) SNR found using sidebands at 230 GHz. Where No Field curve disappears, no stable bias was possible.

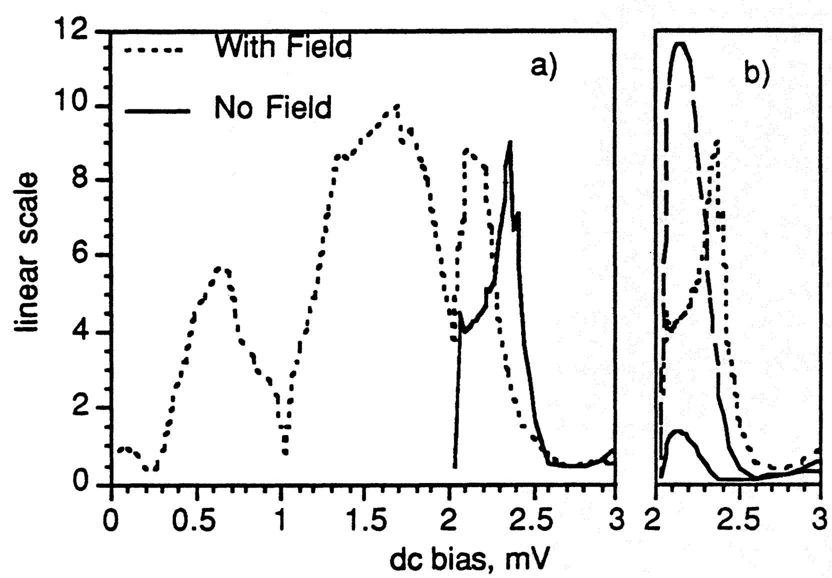

Figure 8) SNR at 492 GHz. a) SNR compared with field on and off. With no field, dc biases between 0 and 2 mV are not stable. b) the dashed line is gain, the solid line is noise, and the dotted line is SNR, done with no field.

Some clues about the nature of the high noise and high gain on S_2 are seen in fig. 8b. The raw data for IF signal (S_{IF}) and noise (N_{IF}) are plotted along with their ratio (SNR) at S_2 and higher dc biases. We see the gain rising quickly as S_2 (at 2 mV) is approached from above. But the noise rises even more quickly as S_2 is approached from above. So the SNR is falling even as gain is rising. The data shown here reinforce the original claim that magnetic field is necessary for submillimeter operation of SIS mixers [10].

Hot and Cold Load Measurement Problems

We described above how an SIS mixer is usually measured using hot and cold blackbodies as calibrated signal sources. In fig. 9, we superimpose gain calculated from hot an cold load measurements with gain measured using a coherent sideband signal. The curves are arbitrarily scaled to be equal at 1.65 mV.

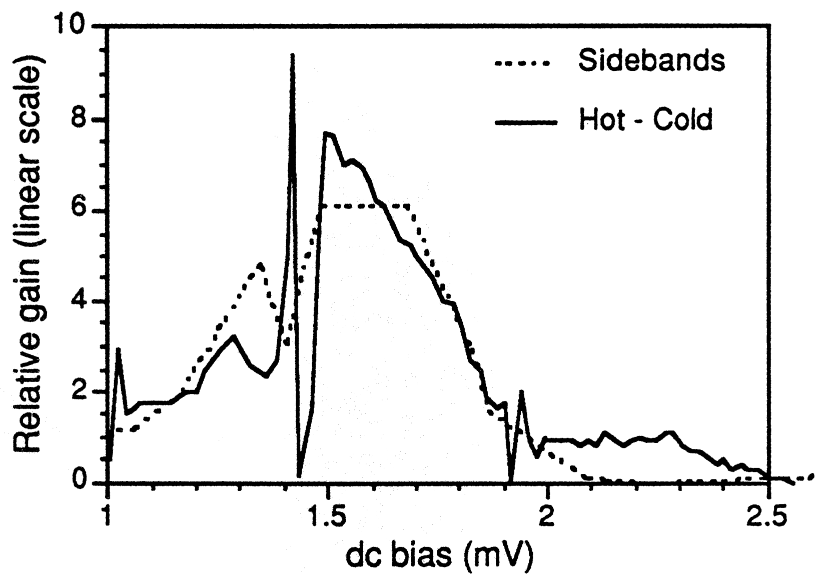

Figure 9 230 GHz relative gain inferred from hot and cold load measurements, and sidebands. The sideband gain here is the same as in fig. 5, but on a linear scale. Curves are scaled to be equal at 1.65 mV. Done with magnetic field on.

The hot and cold load method produces some wild structure near S_3 and S_4. It also overestimates gain at dc biases above 2 mV. Measurements of gain with sidebands showed that the mixer gain was actually quite smooth through the Shapiro steps, and was quite low at voltages above 2 mV. We believe that the reason for this deviation is non-linear response of the SIS mixer to the blackbody radiation, as discussed above. Essentially, the SIS is acting as a noise generator where the magnitude of its generated noise varies as the magnitude of broadband noise from the blackbody is changed. Above 2 mV, we may actually be seeing the effects of direct detection by the SIS of the hot and cold load radiation. A detector current has fluctuations in it which reflect the statistics of the incident radiation. Even a small detected current from a hot thermal source may have a fairly large amount of fluctuation, since thermal sources have large fluctuations.

The conditions under which the SIS is most apt to act as a noise generator are 1) high frequency operation (it seems to be more of a problem in the submillimeter than in the millimeter), 2) broadband coupling structures: low capacitance SIS's coupled to planar antennas will be coupled to hundreds of GHz of blackbody noise, and 3) strong Josephson effects, especially if the SIS is biased very near to one of the Shapiro steps S_n.

The sideband and two-oscillator techniques are not susceptible to the same kind of misinterpretation between excess noise vs. actual down-conversion. A narrow band IF signal cannot be produced by any other mechanism than linear down-conversion of a narrow band signal. Our effort with sidebands may result in more reliable and simpler ways of calibrating SIS mixers. At minimum, we will develop protocols for verifying that mixer noise is not being mistaken for signal.

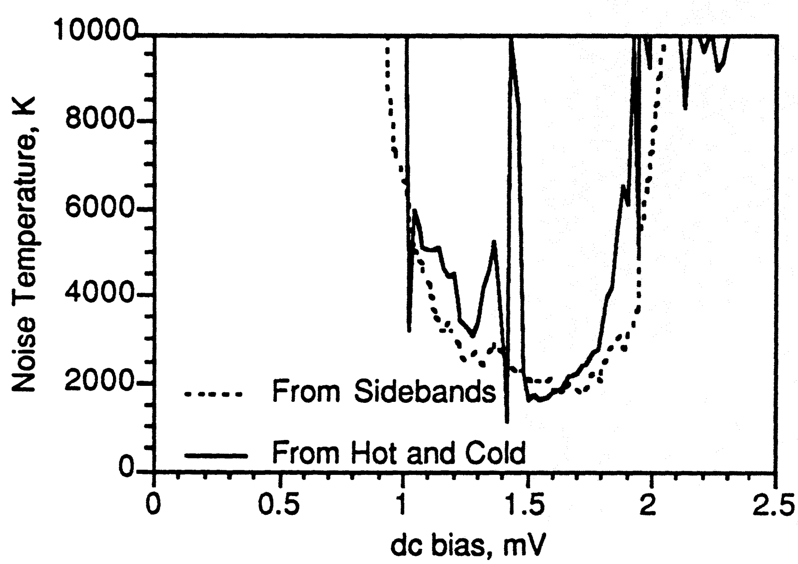

Figure 10) Noise temperature at 230 GHz calculated from hot and cold load measurements is shown as a solid line. The dashed line shows a/SNR where a is a scaling constant and SNR is from sidebands as shown in fig. 7.

Hot and cold load measurements establish mixer noise temperature. The solid line in fig. 10 shows the noise temperature of a 230 GHz receiver as dc bias is varied. The dashed line is a graph of 1/SNR measured with sidebands, multiplicatively scaled so that it fits the solid line. The region of low noise shows good overlap with Q_1, the first quasiparticle photon step below the SIS gap voltage.

Even with magnetic field applied to suppress Josephson currents, we see glitches in the hot-cold measurement at all Shapiro steps near Q_1. Magnetic field is not able to fully suppress Josephson currents. More importantly, it does not suppress them enough to remove non-linear response to hot and cold loads. But again, the sideband measurement shows a smooth variation of mixer noise temperature through the Shapiro steps.

Because of the high receiver noise temperature at 492 GHz, gain and noise calculated from hot and cold load measurements were too noisy to use. We anticipate that the problems we report for hot and cold measurements at 230 would be much worse for 492 GHz. We expect to make better measurements at 492 GHz when we have a lower noise receiver.

Summary

SIS mixers at submillimeter frequencies are much more influenced by the presence of Josephson currents and Shapiro steps than are lower frequency mixers. At 492 GHz, twice as much gain is available when Josephson currents are not suppressed by magnetic field. Unfortunately, this high gain is associated with an even higher noise in these mixers, so that maximum signal to noise at 492 GHz is achieved with a magnetic field present to suppress Josephson currents.

The SIS mixer at 230 GHz has about the same gain available whether or not its Josephson effect currents are suppressed by magnetic field. It has lower noise at some biases when no field is applied, but those low noise regions are very narrow and might be difficult to use in a radio-astronomical receiver. But the trend in which it is more important to apply magnetic field to higher frequency SIS mixers is clearly seen comparing 230 and 492 GHz SIS mixer results here.

We have described two useful methods for measuring relative gain and noise in SIS mixers. One of these methods uses two oscillators, one as LO and one as signal. The other requires only a single submillimeter source, which is modulated at the IF so that it serves as both LO and signal. We have discussed how to make these measurements absolute by calibrating them with hot and cold load measurements. We have shown that the Amplitude Model of SIS mixing can be used to predict relative gain even without mixing measurements.

We have discussed the relation of sideband-measured relative gain and noise to hot and cold load measurements. We have described how hot and cold load measurements can err, particularly near Shapiro steps, and have shown direct measurements of the errors at 230 GHz. We have suggested these effects will be much stronger at 492 GHz. We have laid the groundwork for SIS receiver calibration schemes which could augment hot - cold load techniques.

Acknowledgements

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