Josephson Effect Gain and Noise in SIS Mixers

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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 1000 GHz. We report measurements of gain and noise in SIS mixers at 230 and 492 GHz. We measure relatively high gain and noise associated with Josephson currents that 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 mixers 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 detectors 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 that has a nonlinearity in its current-voltage curve (IV) at 0 V. The quasiparticle-device has an IV similar to the forward conduction IV of a regular diode. It has a nonlinearity in its IV at its gap voltage, V_{GAP}. We are working with lead alloy SIS junctions. The IV for our lead alloy junction can be seen in both Fig. 1 and Fig. 2. The pair and quasiparticle nonlinearities are both present. 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. 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.

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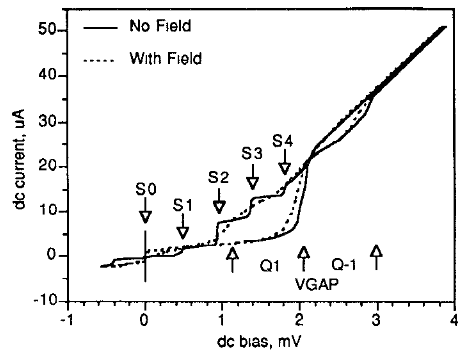


Fig. 1. SIS IV curves with and without 230 GHz radiation applied. The dashed lines are with magnetic field applied to suppress the Josephson effect, the solid lines are without. Shapiro step voltages and quasiparticle photon steps are shown.

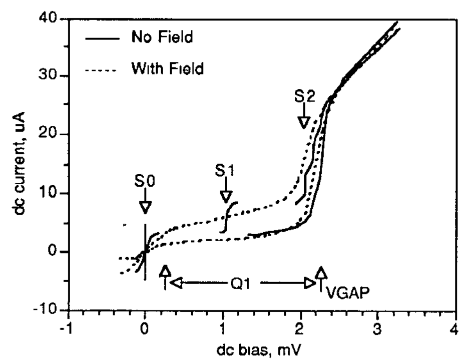


Fig. 2. SIS IV curves with and without 492 GHz radiation. The dashed lines are with a magnetic field applied, solid lines are without. Broad ranges of dc bias are not possible unless a magnetic field applied.

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 36 GHz. 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.

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 millimeter wavelengths, best SIS mixing performance occurs for a dc bias on Q_1 a few tenths of a millivolt below V_{GAP}. At 230 GHz, Fig. 1 shows 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 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 the Josephson effect pair currents as the frequency of SIS mixer operation is increased.

Quasioptical SIS Mixer

For work investigating SIS mixer performance over a broad range of millimeter and submillimeter wavelengths we use a radiation coupling structure that works over this whole 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].

The receiver at Caltech has been operated at 492 GHz with receiver noise temperatures below 1500 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 expect the effects we report here will be present in lower noise SIS mixers.

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,

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

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 is linear only if N_{IF} is constant as T_L is varied. 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. The hot and cold load method of receiver measurement does not have a large dynamic range.

Second, N_{IF} may change as T_L is changed. In that case, the change in P_{IF} is not due to linear mixing. Ignoring this possibility leads to underestimates of T_N. We have operated mixers in the laboratory where this effect was so severe that a naive application of linear mixer theory lead to calculations of $T_N < 0$ K! Nonlinear 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 problem with using blackbodies as calibration signals is that they are incoherent sources. There is no way to distinguish, at the mixer output, between the part of P_{IF} which comes from down-conversion of S_{RF}, and the part which is just 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. What is more important, 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 are big and multimoded. But the coherent source radiates into only a single mode of the radiation field that must be made to overlap with the radiation mode to which the mixer responds.

We make measurements assuming that our signal oscillator power is unknown, but constant in time. These are not absolute measurement of gain or noise temperature. We can measure how gain and noise change as the following are varied: LO power level, dc bias voltage, and magnetic field strength.

All the relative measurements of gain and noise can be calibrated absolutely if one unsaturated hot and cold load mixer measurement can be made. A mixer operated with magnetic field applied and dc bias voltage near V_{GAP} will have minimal Josephson effect interference and fairly low gain. A hot and cold load measurement made under this bias condition can be assumed to be unsaturated in the absence of other evidence to the contrary. This unsaturated hot and cold load measurement can calibrate a coherent signal measurement made under the same conditions. By relating this to coherent signal measurements, absolute gain and noise temperature can be made for all mixers under all conditions.

Two Oscillators

The simplest and most versatile way to measure gain and noise of a mixer with a coherent signal is to use two rf oscillators. One acts as LO and one provides 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. However, astronomical groups will often keep extra oscillator systems around as backups. Also, older or cheaper sources that have insufficient power output to serve as LO's can still serve as signals.

Sidebands

A cheaper way to produce coherent signal is to modulate the LO source with a low power source at the IF frequency. The radiation leaving the oscillator will now have low power sidebands spaced an IF frequency away from the LO. These sidebands are at the mixer's signal and image frequencies.

It is easy to modulate 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 the desired sidebands. Sideband intensity with respect to the LO is controlled by varying the amplitude of the 1.5 GHz diode modulation.

We think that virtually any LO source can be made to produce sidebands. The work reported here is done with by modulating Schottky-diode triplers (for 230 GHz) and quintuplers (for 492 GHz). We have generated sidebands directly on one of our 3 mm Gunn sources by superimposing a small 1.5 GHz signal on its dc power supply. 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 230 GHz.

One measurement that can be made with two oscillators that is more difficult 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 a change of IF power out of the mixer is no longer simple to interpret as a mixer gain change. However, if the LO and its sidebands were passed through a calibrated attenuator, the change in signal power would be known as the LO power was varied. It would be possible to measure how gain varies with LO power applied using the sideband method and a calibrated attenuator.

Gain at 492 GHz

Fig. 3 shows gain measurements at 492 GHz as LO power is varied. The measurements on S_0 and S_2 are made with no magnetic field applied to the SIS. Bias on Q_1 corresponds to the usual way an SIS is operated at millimeter wavelengths. A magnetic field is applied to suppress Josephson currents for the measurement of gain on Q_1. The maximum gain with no magnetic field applied is over twice as high as with field applied. That maximum gain occurs for a bias at the high-current end of the Shapiro steps S_0 and S_2. 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.

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 a dc bias of 1.6 mV. Relative gain is 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. 4 dB more gain is available on S_2 then on Q_1. 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. We could also 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 that rely on a phase modulation of the LO by the signal. Our sideband system might mismeasure 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

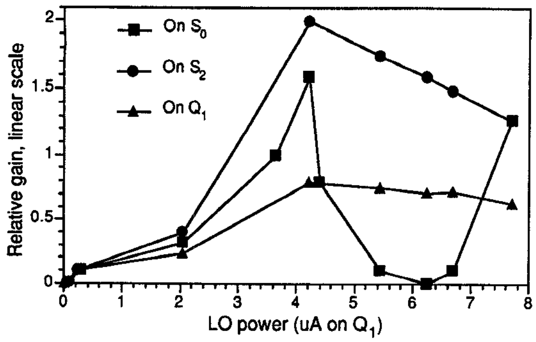


Fig. 3. Relative gain at 492 GHz is measured as LO power is increased. Two of these curves are for bias points at the gain maxima near S_0 and S_2, with no magnetic field. The third is at the gain maximum of Q_1 with magnetic field.

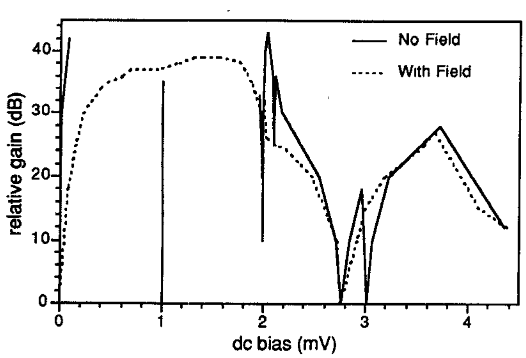


Fig. 4. Relative gain at 492 GHz with and without magnetic field applied to suppress Josephson effects.

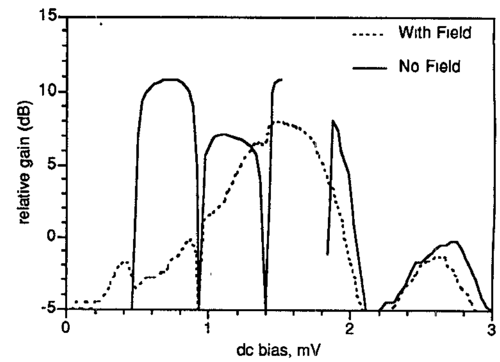


Fig. 5. Relative gain at 230 GHz, with and without magnetic field to suppress Josephson effect.

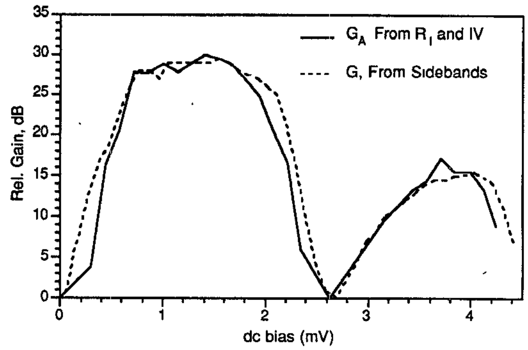


Fig. 6. Relative gain at 492 GHz, measured with sidebands and calculated from IV curve measurements.

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 where we thought there might be parametric mixing. Since both methods give identical gain measurements, we conclude that there is no parametric mixing.

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_3 and S_4 showed gain that was visibly fluctuating on the spectrum analyzer. We show gain with no field only where we found it to be stable. With magnetic field applied, miser gain is stable at all dc bias voltages. The higher mixer gain is found with no field applied, as it was at 492 GHz. However, the gain is only 2.8 dB higher at 230 GHz as opposed to 4 dB higher at 492 GHz.

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.

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 in the SIS,

$$I(t) = R_I P_{RF}(t).$$

The ω_{IF} component of this is coupled out of the mixer 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. These measurements were made 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

Fig. 7 shows the SNR calculated from coherent signal measurements at 230 GHz. The maximum gain with no field is 90% higher than the gain with magnetic field applied (Fig. 5), but the best SNR of the mixer without field is only 40% better. The peaks of high SNR occur at dc bias voltages very close to S_3 and S_4, where gain is also high.

SNR at 492 GHz

Fig. 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 less than half as much.

Details of the nature of the high noise and high gain on S_2 are seen in Fig. 8(b). 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. Thus, 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 230 GHz gain calculated from hot and cold load measurements with gain measured using a coherent sideband signal. The curves are arbitrarily scaled to be equal at 1.65 mV.

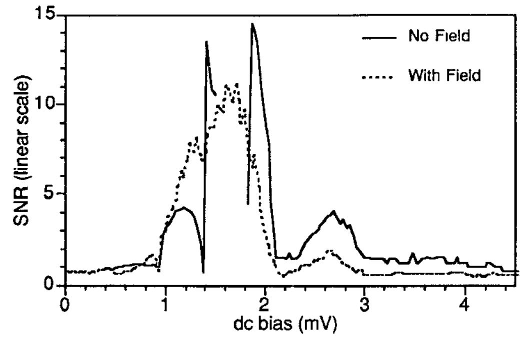
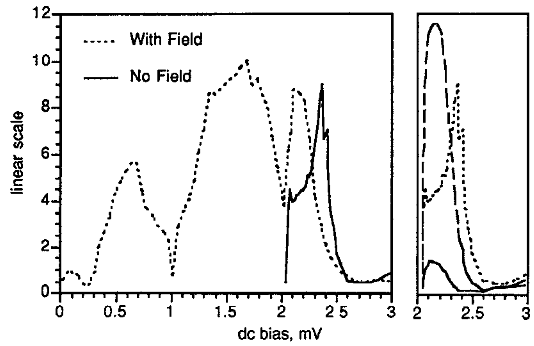


Fig. 7. SNR found using sidebands at 230 GHz. Where the no field curve disappears, no stable bias was possible.



(a) (b)

Fig. 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.

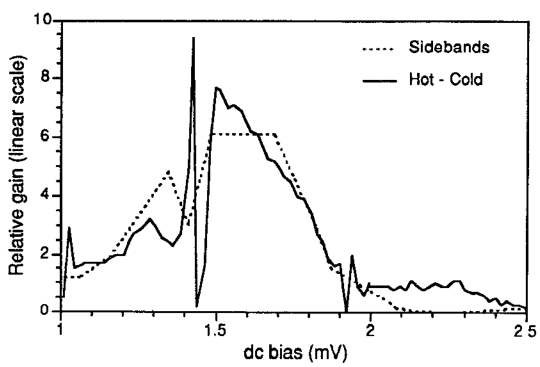


Fig. 9. 230 GHz relative gain inferred from hot and cold load measurements, and sidebands. The sideband gain here is the same as in Fig. 5, but on a linear scale. Curves are scaled to be equal at 1.65 mV. Done with magnetic field on.

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 nonlinear response of the SIS mixer to the blackbody radiation, as discussed above. Essentially, the SIS is acting as a noise generator. The magnitude of its generated noise rises as the temperature of the blackbody illuminating it increases.

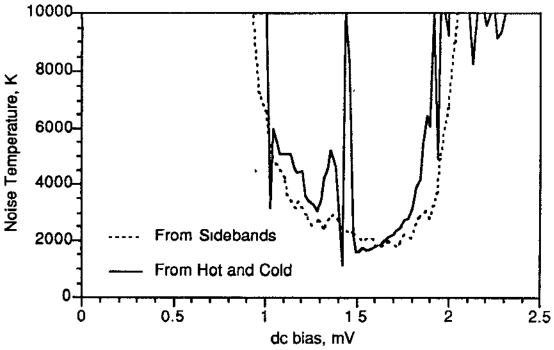


Fig. 10. Noise temperature at 230 GHz calculated from hot and cold load measurements is shown as a solid line. The dashed line shows a/SNR where a is a scaling constant and SNR is from sidebands as shown in Fig. 7.

Above 2.2 mV, the sideband measurements show that mixer gain has gone to zero. But the SIS still responds to blackbody radiation with IF power that rises with blackbody temperature! This IF power is clearly not due to heterodyne downconversion. What we may be seeing here is noise from the direct detection of the photons leaving the blackbody. The direct detection current has fluctuations in it that reflect the fluctuations of the incident radiation. The fluctuations in power from a blackbody rise as the blackbody's temperature rises.

The sideband and two-oscillator techniques are not susceptible to the same kind of misinterpretation between excess noise versus 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.

Receiver noise temperature is calculated from hot and cold load measurements. 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, scaled so that it fits the solid line. The agreement between the two measurements of receiver sensitivity is good.

Even with magnetic field applied to suppress Josephson currents, we see glitches in the hot-cold measurement at all Shapiro steps near Q_1. The sideband data, however, are smooth. Apparently, there is non-linear response to hot and cold loads, especially in the vicinity of Shapiro steps. Even with magnetic field applied, the mixer suffers from strong non-linear effects due to Josephson pair currents.

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 GHz 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 wavelengths are much more influenced by the presence of Josephson currents and Shapiro steps than are lower frequency mixers. At 492 GHz, more than twice as much gain is available when Josephson currents are not suppressed by magnetic field. Unfortunately, there is also about four times as much noise, so that the maximum SNR at 492 GHz is achieved with a magnetic field present to suppress Josephson currents.

The SIS mixer at 230 GHz has 2.8 dB more gain available when no magnetic field is present to suppress Josephson effect currents. At 230 GHz, the higher gain mixer has the higher SNR, but the SNR advantage is only 1.5 dB. 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 that could augment hot-cold load techniques.

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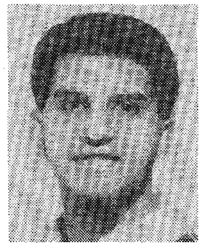
Dr. Wengler is a member of the American Physical Society and the Microwave Theory and Technique Society Speaker's Bureau. He is Treasurer of the Electron Devices Society of Rochester.



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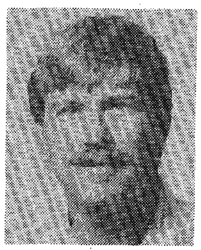

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