Shot Noise and Photon-Induced Correlations in 500 GHz SIS Detectors

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***Abstract* — Photon-induced current correlations in SIS detectors can result in an output noise that is greater or less than shot noise. Evidence of these correlations had been observed for 100 GHz rf by accurate noise measurements as reported in our previous work. We now present a detailed analysis of these current correlations for frequencies between 100 and 500 GHz. We also report new measurements of photon-induced noise in a 490 GHz SIS mixer, and discuss the Gaussian beam techniques used to eliminate the thermal background radiation. For small 490 GHz rf power, the output noise is equal to shot noise. The results of the 100 and 490 GHz photon noise measurement are summarized in context to shot noise and the effect of the current correlations predicted by the theoretical model.**

I. INTRODUCTION

With no incident radiation, the noise in the tunneling current of an SIS junction is given by shot noise: $<i^2> = 2eI_0B$, where I_0 is the dc tunneling current and B is the measurement bandwidth. Shot noise implies independent tunneling of the quasiparticles across the junction barrier. With incident radiation, rf current correlations between the mixer's sideband currents can result in deviations from shot noise. These photon-induced correlations between tunneling quasiparticles are predicted by Tucker's theory [1] and can be measured in the output noise. The effect of these correlations at 100 GHz has been measured in our previous work [2]. We now investigate and measure the effect of these correlations at higher frequencies.

We measure the response of the SIS junction to a pure radiation field, or of an SIS mixer with no signal input. Measurement of the output noise of a pumped SIS mixer with no signal input is the most direct measurement of the mixer's intrinsic noise. Since the rf radiation is produced outside the dewar at room temperature, some of the 295 K thermal background radiation will be coupled to the SIS junction along with the rf. This thermal radiation will act as an input signal and thus must be eliminated by injecting the rf through a cold rf load. At 500 GHz the rf injection is done quasi-optically as described in section III.

II. THEORETICAL ANALYSIS

A. Theoretical Model

The noise is calculated using Tucker' theory [1] in addition to a vacuum/thermal noise term [3]. A three-port model is used, which assumes that the higher harmonics of the local oscillator and the corresponding sidebands are shorted out by the junction capacitance. The total ouput noise of the SIS mixer is given by:

$$\langle i_T^2 \rangle = \langle i_{eq}^2 \rangle + \langle i_{vt}^2 \rangle \tag{1}$$

where,

$$\begin{aligned}\langle i_{eq}^2 \rangle = B\,[\,&H_{00} + 2(\lambda_{01} + \lambda_{01}^{*}\ )H_{10} \\ &+ (\lambda_{01}^2 + \lambda_{01}^{*\,2})H_{1\text{-}1} + 2\,|\lambda_{01}|^2\,H_{11}\,]\end{aligned} \tag{2}$$

and

$$\langle i_{vt}^2 \rangle = 4BG_s\,|\,\lambda_{01}\,|^2\hbar\omega\ \ \coth\frac{\hbar\omega}{2kT}\,. \tag{3}$$

The first term, $<i_{eq}^2>$, consists of the shot noise in the junction's leakage current and the noise in the photon induced current. This term is computed by placing current noise generators at the upper and lower sideband inputs of the mixers, which are represented by an equivalent current noise generator of amplitude i_{eq} at the output [4]. Since the sideband noise currents are correlated, they can interfere to add or subtract from the total noise. $H_{mm'}$ are the elements of the current correlation matrix evaluated in [1], λ_{01} characterizes the conversion efficiency of the mixer from the signal sideband to the output port, and B is the measurement bandwidth.

The second term, $<i_{vt}^2>$, contains the noise due to vacuum and thermal fluctuations at the signal and image frequencies, which is down-converted to the output [3]. This noise is not correlated with $<i_{eq}^2>$. G_s is the real part of the source admittance Y_s, ω is the rf frequency, and T is temperature at which the input sidebands are terminated. Two additional assumptions are made. The mixer is assumed to be equally sensitive to signals in the upper and lower sidebands so that $\lambda_{01} = \lambda_{0\text{-}1}^*$ and $Y_{-1} = Y_1^* = Y_s$; and the output frequency ω_0 is assumed to be much smaller than ω.

The measured IV-curve of a high quality Nb-AlO$_x$-Nb junction was used for the theoretical calculations. The normal resistance of this junction is 21 Ω and the gap voltage is 2.9 V at 4.28 K. The source impedance is assumed to be that of a 75 Ω antenna in parallel with the junction capacitance.

B. Output Noise with zero junction capacitance

For these calculations the junction capacitance is assumed to be perfectly tuned out by an integrated tuning circuit. The

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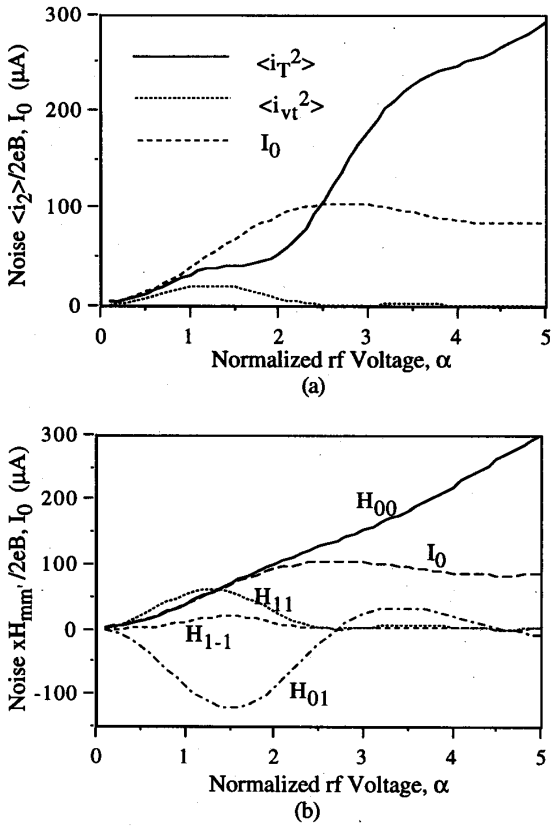

Fig. 1. (a) Output noise as a function of the normalized rf voltage across the junction, as calculated from equations (1)-(3), and the dc tunneling current I_0. (b) The current correlation terms shown in equation (3), including the effects of the conversion factor λ_{01}.

The source impedance is then that of a 75 Ω broadband antenna. The temperature at the input sidebands is taken to be 4.28 K, and the dc bias corresponds to the middle of the first photon step.

The total output noise is calculated using equations (1)-(3) for 500 GHz rf and is plotted as a function of the normalized rf voltage α in Fig. 1a. $\alpha = eV_\omega/\hbar\omega$, where V_ω is the amplitude of the rf voltage across the junction. The noise is expressed in units of current as $<i^2>/2eB$ so that the comparison to shot noise can be made by simply comparing it to the calculated dc tunneling current I_0. Also plotted in Fig. 1a is the vacuum/thermal contribution to the total noise given by (3).

For small rf voltage ($\alpha < 0.8$) the total output noise is predicted to be equal to shot noise, and the contribution from the vacuum/thermal fluctuations at the input is approximately half of the total noise. For larger rf voltages, large deviations from shot noise are predicted due to the increasing effect of the current correlation terms in (2). The four terms in (2) are plotted in Fig.1b along with I_0 for comparison to shot noise. The cross correlation terms including H_{01} and H_{1-1} can make negative contributions to the noise, as seen in Fig. 1b. For $\alpha < 1.5$, the first term BH_{00} is found to be exactly equal to shot noise but remaining correlation terms in (2) make an overall negative contribution, resulting in a $<i^2_{eq}>$ that is less than shot noise for small α.

We note that for zero rf power ($\alpha = 0$), the conversion factor $\lambda_{01} = 0$ and the only non-zero term in the total output noise is BH_{00} which reduces to shot noise for $\alpha = 0$. Thus Tucker's theory implicitly assumes that the noise in the leakage current is pure shot noise. For non-zero α, H_{00} deviates from shot noise as α and rf frequency increase, as is seen in Fig.1b. This deviation is due to quantum fluctuations.

The total output noise as a function of rf voltage is then calculated for the same junction for several rf frequencies between 100 and 500 GHz. In each case the junction bias is set to the middle of the first photon step, and the junction capacitance is assumed to be completely tuned at the rf frequency. The results are displayed in Fig. 2. The total output noise of the SIS does not vary much with frequency for $\alpha \leq 1$. This is consistent with the output noise temperature of an SIS mixer being independent of frequency for small α [5]. For larger rf power the output noise at the different frequencies is radically different due to the varying effect of the current correlations and the quantum fluctuations.

B. Effect on junction capacitance on the output noise

We will now investigate the effect of non-zero junction capacitance on the total output noise at 500 and 100 Ghz, as plotted in Figs. 3a and 3b respectively. The dc biases corresponds to the middle of the first photon step, and the junction capacitance is assumed to be in parallel with a 75 Ω antenna.

For 500 GHz rf the total noise is calculated for capacitances ranging from 0 to 100 fF. The junction capacitance effects the conversion properties and thus determines the effect of the current correlation terms. For $\alpha < 0.7$ the junction capacitance has almost no effect on the total output noise. As the capacitance increases the total noise approaches H_{00}, due to the diminishing conversion

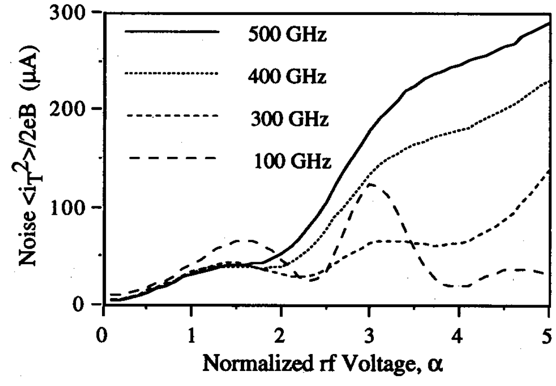

Fig. 2. Output noise as a function of normalized rf voltage for different rf frequencies. In each case the dc bias is on the middle of the first photon step and junction capacitance is assumed to be zero.

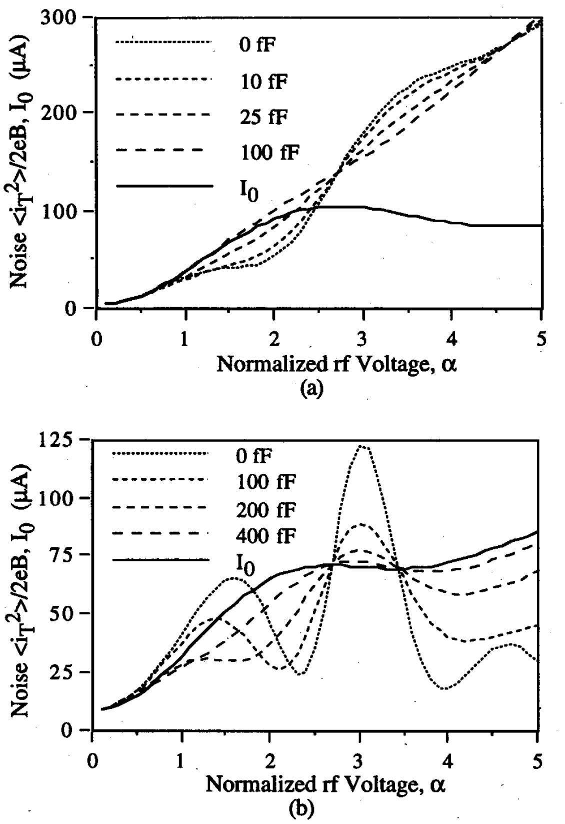

Fig. 3. Calculated output noise as a function of normalized rf voltage for (a) 500 GHz and (b) 100 GHz incident rf, for several values of junction capacitance.

gain. We note that output noise is independent of junction capacitance at rf voltages corresponding to the critical points of the $I_0(\alpha)$ curve, where $dI_0/d\alpha = 0$. This is due to zero current responsivity at these points, which results in zero conversion gain.

For 100 GHz rf, junction capacitances ranging from 0 to 400 fF have little effect on the output noise for $\alpha < 0.6$. At larger rf voltages the total noise shows a strong dependence on the junction capacitance which is largely due to the current correlations. As the capacitance increases the total noise approaches shot noise which is equal to H_{00} at 100 GHz.

III. EXPERIMENTAL DETAILS

A. Junction and Integrated tuning circuit

The SIS mixer circuit used for the 490 GHz noise measurement consists of a 2-junction integrated tuning circuit coupled to the rf via twin slot antennas. Details of the tuning circuits and the twin-slot antenna may be found in [6] and [7]. Each of the Nb-AlO$_x$-Nb junctions has an area of ~3.4 μm^2, and normal resistance of 5.8 Ω. The junctions appear in parallel at dc so that the R_n for the junction circuit is 2.9 Ω. This quasi-optical twin-slot mixer circuit is mounted on the plane surface of a quartz hemisphere which maintains the broad beam pattern of the twin-slot antenna.

B. Quasi-optical rf injection

Quasi-optical beam mismatch is used to eliminate the thermal background radiation. The rf oscillator and antenna beams are intentionally mismatched so that a very small fraction of the 295 K background radiation is coupled to the antenna. The quartz hemisphere, with the twin slot antenna attached, is surrounded by a 4.2 K absorbent cavity, as shown in Fig. 4. The potter horn of the 490 GHz multiplier produces a gaussian beam which is focused on the SIS antenna through a aperture in the 4.2 K cavity. w_1, w_2, and w_3 represent the Gaussian beam contours corresponding to 1/e of the electric field strength. Most of the antenna's diverging beam is coupled to the 4.2 radiation of the cavity walls. Using the known gaussian beam characteristics of the antenna and oscillator beams, the power coupling coefficient between the two gaussian beams can be calculated [8]. By moving the position of the quartz lens within the physical constraints, a power coupling coefficient K_{12} between 0.006 and 0.048 can be achieved [9]. For the 490 GHz measurement $K_{12} = 0.037$, which implies 11 K of background radiation coupled to the antenna.

C. 1.5 GHz noise measurement system

The low-noise cryogenic measurement system that is used to measure the 1.5 GHz output noise is described in [2]. This system is capable of accurate measurement of the system noise and gain, and of the reflection coefficient at the SIS, thus providing a calibrated measurement of the available noise power at the SIS output. The measured noise temperature of the 1.5 Ghz system for this measurement is 4.35 K in a 400 MHz bandwidth. All significant reflection and transmission losses are taken into account in calculating the available power at the mixer output [9]. The estimated measurement error is calculated for each measured data point.

VI. MEASUREMENT RESULTS FOR 490 GHz RF

The measurement of output noise as a function of the dc voltage bias shows good agreement with the theoretical noise, as shown in Fig. 4. The 490 GHz rf power corresponds to

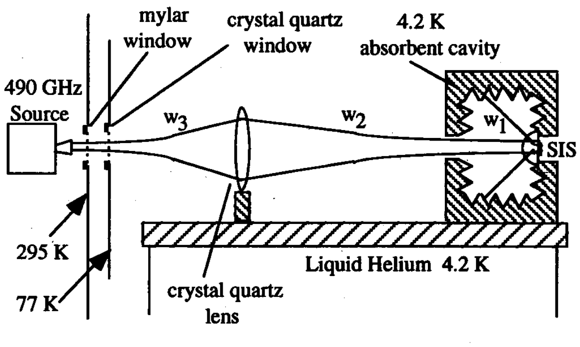

Fig. 4. Schematic diagram of rf injection set-up for 490 GHz

$\alpha = 0.35$. The theory is shot noise augmented by the effect of the 11 K thermal background radiation. The peaks in the measured noise at 1 and 2 mV correspond to the positions of the 490 GHz Shapiro steps. The applied magnetic field was not enough to suppress these Josephson effects. The error bars are large at and above the gap voltage due to the impedance mismatch between the SIS device, with $R_n = 3\ \Omega$, and the noise measurement system, which is optimized for $50\ \Omega$. The measurement error increases as the reflection coefficient, due to this mismatch, increases.

The noise measured as a function of normalized rf voltage is plotted in Fig. 5b. The junction biased at 1.63 mV on the middle of the first photon step. The effect of the 11 K thermal background is subtracted from the measured noise and the adjusted measured noise for a 4.2 K background is plotted against the pure shot noise. We find that the measured output noise is equal to shot noise, for a 4.2 K thermal background. Unfortunately the rf voltage could not be increased beyond $\alpha = 0.35$ due to the limited power available from the rf oscillator. Thus we could not explore the effects of the current correlations which are predicted to occur for $\alpha > 1$.

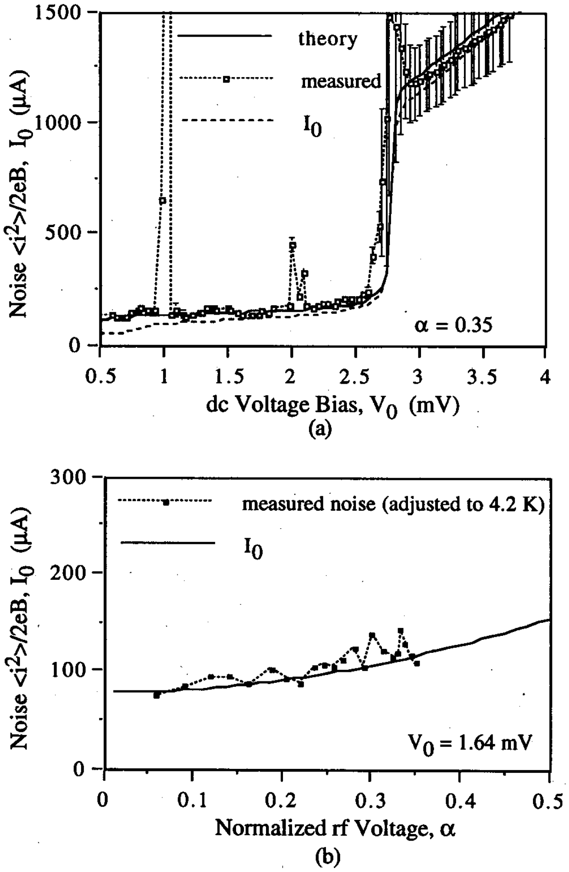

Fig. 5. (a) Measured output noise as a function of dc bias voltage for an SIS mixer circuit radiated with 490 GHz rf, for $\alpha = 0.35$. (b) Measured noise as a function α, for $V_0 = 1.64$ mV.

V. DISCUSSION AND CONCLUSIONS

We have made a detailed theoretical and experimental analysis of the output noise of niobium SIS junctions radiated with 100-500 GHz radiation and a 4.2 K thermal background. Our calibrated noise measurements have verified several predictions of the theoretical model.

For small rf power, corresponding to $\alpha < 0.7$, the output noise is equal to shot noise, which implies no correlation between the rf currents or the tunneling quasiparticles. This has been verified at 100 GHz previously [2], and at 500 GHz by the measurements presented in this paper. This result for small rf power is independent of the junction capacitance or source impedance presented to the mixer. Furthermore, for small alpha the output noise is independent of frequency.

For larger rf power, corresponding to $\alpha > 1$, photon induced correlations can have a large effect on the output noise, causing large deviations from shot noise. The effect of these correlations has been experimentally verified for 100 GHz rf [2], but could not be verified at 500 GHz due to insufficient rf power. These current correlations and hence the output noise are affected by the junction capacitance for large α. This variation of output noise with source impedance has been observed in SIS junctions radiated by 100 GHz photons, by using junctions with and without integrated tuning circuits [2].

For practical SIS mixers in the 100-500 GHz range, the optimum rf voltage is close to $\alpha = 1$. Provided that the thermal background radiation has been minimized, shot noise is still a good approximation for the total output noise.

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