Performance of Arrays of SIS Junctions in Heterodyne Mixers

DENIS-GERARD CRÉTÉ, WILLIAM R. MCGRATH, PAUL L. RICHARDS, AND FRANCES L. LLOYD

Abstract —We have made a systematic experimental study of the performance of millimeter-wave quasiparticle heterodyne mixers which use arrays of SIS tunnel junctions. Sets of arrays with $N=1$, 5, 10, 25, and 50 junctions in series were fabricated by photolithography. All of the arrays in a given set were made on a single silicon wafer so that their response time parameter $\omega_S R_N C$ would be the same. Junction areas were scaled so that the total impedance was the same for each array in a set. Sets of arrays from four wafers with values of $\omega_S R_N C$ ranging from 2.6 to 13 were evaluated in mixers at 33 and 36 GHz. These measurements showed that the signal power required to saturate the mixers varies as N^2 and that the conversion efficiency is nearly independent of N for all values of $\omega_S R_N C$. The mixer noise temperature is independent of N for large values of $\omega_S R_N C$. Therefore, the dynamic range of an SIS quasiparticle mixer can increase in proportion to N^2. For small values of $\omega_S R_N C$, however, the mixer noise increases systematically with N. This correlation suggests that the junction capacitance affects the coupling between junctions that can contribute to the noise.

I. Introduction

THE SIS QUASIPARTICLE tunnel junction has been demonstrated to be the most sensitive mixing element for millimeter-wave receivers [1], [2]. Quantum effects [3], [4], such as conversion efficiency (gain) greater than unity, as well as noise temperatures close to the quantum limit, have been observed [1], [4]. Local-oscillator power requirements are as small as 10^{-8} W, which is convenient for some applications but leads to a low saturation threshold for these mixers [5], [6]. For RF bandwidths in excess of 20 percent, saturation can occur on room-temperature noise [5], [6].

During the early development of the Josephson-effect parametric amplifier [7], it was recognized that the use of arrays of Josephson junctions in series could increase both the saturation level of the device and the pump power required. The applicability of this idea to SIS quasiparticle mixers was immediately recognized [8], [9]. The practical benefits of using series arrays are sufficiently important that a substantial number of experiments using arrays have been reported [2], [6], [9]–[11]. It has not been clear, however, whether the use of arrays has caused any sacrifice in mixer gain or noise. In this paper, we report a systematic experimental investigation of mixing with arrays of N junctions in series, where $N=1$, 5, 10, 25, and 50. Two preliminary reports of some of these measurements have been presented [12], [13].

The product of the signal frequency ω_S, the junction normal state resistance R_N, and the junction capacitance C is an important operational parameter for quasiparticle mixers. It depends on the thickness of the tunneling barrier but not on the junction area. Thus, the value of the $\omega_S R_N C$ product is the same for each set of arrays fabricated on a single silicon wafer. The sets of arrays described here had as many as five different values of N. In order to minimize differences in RF coupling to these arrays, the junction areas were scaled in proportion to N. Therefore, the total resistance and capacitance of each array in a set is only weakly dependent on N. The junction areas in a given array were kept as uniform as possible in order to operate each junction with the same dc bias. The overall array lengths were kept short to help ensure that the instantaneous RF current is the same for all junctions.

An equivalent circuit transformation can be used to understand how signals are processed in an SIS array mixer [11]. The individual junctions are modeled by three parallel conducting paths, which correspond to the nonlinear resistance and reactance of the quasiparticle current and also the displacement current through the geometrical junction capacitance. The junctions are joined in series with some series lead inductance, as shown in Fig. 1(a). If the junctions of the array are identical and the phase of the current is constant along the array, then the instantaneous currents are the same in each current path of each junction. In this idealized case, the circuit of Fig. 1(a) can be transformed to that of a single effective junction with the total impedance of each conducting path equal to N times that of a single junction of the array, plus a total series lead inductance, as shown in Fig. 1(b).

Quantum mixer theory applied to this model can be used to compare the performance of mixers based on arrays whose junction areas are scaled in proportion to N. If the embedding impedances are held constant, except as

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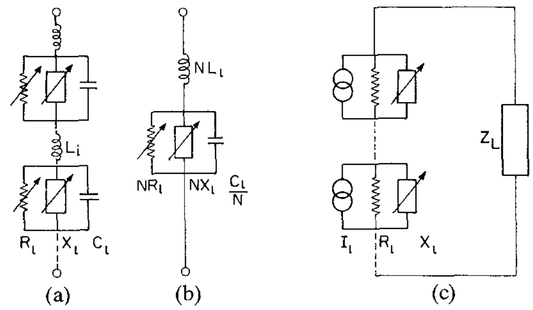

Fig. 1. Equivalent circuits used to compute dependence of mixer performance on the number N of junctions in the array. (a) Equivalent circuits for individual SIS mixers showing parallel conduction paths for nonlinear resistive and reactive quasiparticle currents and linear displacement currents. (b) Effective junction model used to compute gain and saturation level of array mixers. (c) Linearized equivalent noise current generators used to compute noise in array mixers by superposition.

TABLE I
IDEAL DEPENDENCE OF JUNCTION AND ARRAY MIXER PARAMETERS ON N FOR CASE IN WHICH JUNCTION AREA IS SCALED AS N

	Each Junction	Entire Array
V_O, V_{IF}, V_{LO}	1	N
I_O, I_{IF}, I_{LO}	N	N
R_O, R_{IF}, R_{LO}	N^{-1}	1
Capacitance	N	1
Mixer gain	1	1
LO power	N	N^2
Saturation power	N	N^2
Noise power	1	1
Dynamic range	N	N^2

required to tune out the lead inductance, the signal power at which saturation occurs and the local-oscillator (LO) power required scale as N^2. The mixer gain is independent of N. Although the Josephson current is usually neglected in the analysis of SIS mixers, the transformation to an effective junction can be carried out even when it is included. Table I summarizes the expected dependence of important mixer parameters on N for this idealized model and also includes a prediction for noise power that will be discussed below.

A number of advantages can be obtained by using arrays of junctions in series as mixers, especially if the mixer noise does not increase with N. The saturation level and the dynamic range can be selected to match the requirements of the experimental application. This can be especially important for those signal-processing applications [14], [15] that use high-level signals. Problems associated with the small junctions required for operation at very high frequencies can be alleviated by the use of arrays of larger junctions. Fabrication requirements are relaxed, sensitivity to burnout is reduced, and Josephson phenomena can be more easily suppressed with a magnetic field [10].

In Section II of this paper, we discuss a simple mathematical model for arrays of N junctions in series; this model predicts that the noise can be independent of N. The design and fabrication of the arrays are described in Section III. The measurement techniques used to evaluate mixer performance are summarized in Section IV. The experimental results are presented in Section V.

II. NOISE CALCULATIONS

If the noise in separate junctions is uncorrelated, the noise in array mixers can be calculated by applying Tucker's theory to the effective junction model described above [16]. To illustrate the expected noise performance, however, we review an analytical model related to discussions found in the literature [5], [11] which gives equivalent results. The Tucker theory for mixer noise in the IF output band is applied to each junction, and the total noise power dissipated in the load is computed by superposition, assuming that the noise in different junctions is uncorrelated. This procedure cannot be used to compute the gain or the saturation level for the array mixer, because the RF embedding impedances for the individual mixers in the array are not known [11]. The effective junction approach described above requires only the embedding impedance of the array and therefore avoids this difficulty.

We represent noise in the ith pumped and biased junction by an IF noise current generator I_i in parallel with a resistance R_i and a reactance jX_i. A series array of such model junctions is assumed to drive a load impedance Z_L as is shown in Fig. 1(c). The current in the load due to the ith model junction is

$$I_{Li} = I_i\left(\frac{Z_i}{Z_L + Z_N}\right) \tag{1}$$

where $Z_N = \Sigma Z_i$ and $Z_i = (1/R_i + 1/jX_i)^{-1}$. If these noise generators are not correlated, the noise power dissipated in the load due to all N junctions is

$$P_L = R_L \sum_i \langle I_{Li}^2 \rangle = R_L \sum_i \langle I_i^2 \rangle \left|\frac{Z_i}{Z_L + Z_N}\right|^2. \tag{2}$$

If all junctions in the array are identical, $Z_i = Z_N/N$ and $\Sigma_i \langle I_i^2 \rangle = N\langle I_i^2 \rangle$. Then

$$P_L = R_L \frac{\langle I_i^2 \rangle}{N}\left|\frac{Z_N}{Z_L + Z_N}\right|^2. \tag{3}$$

The impedance ratio in (3) is independent of N for the arrays scaled as in Table I. To determine the dependence of $\langle I_i^2 \rangle$ on N, we must properly consider correlated noise sources at the IF, signal, and image frequencies in each junction. If we neglect zero-point noise, we can use the expression for the noise current in bandwidth B at the IF output derived by Tucker [17]:

$$\langle I_i^2 \rangle = B \sum_{m,m'} \lambda_{0m} \lambda_{0m'}^* H_{mm'}. \tag{4}$$

The normalized impedance matrix elements $\lambda_{mm'}$ depend only on impedance ratios and therefore are independent of N. The correlation matrix H scales as N; therefore, from (3) the coupled noise power P_L is independent of N. Since the gain is independent of N, the input noise temperature of the mixer is predicted to be independent of

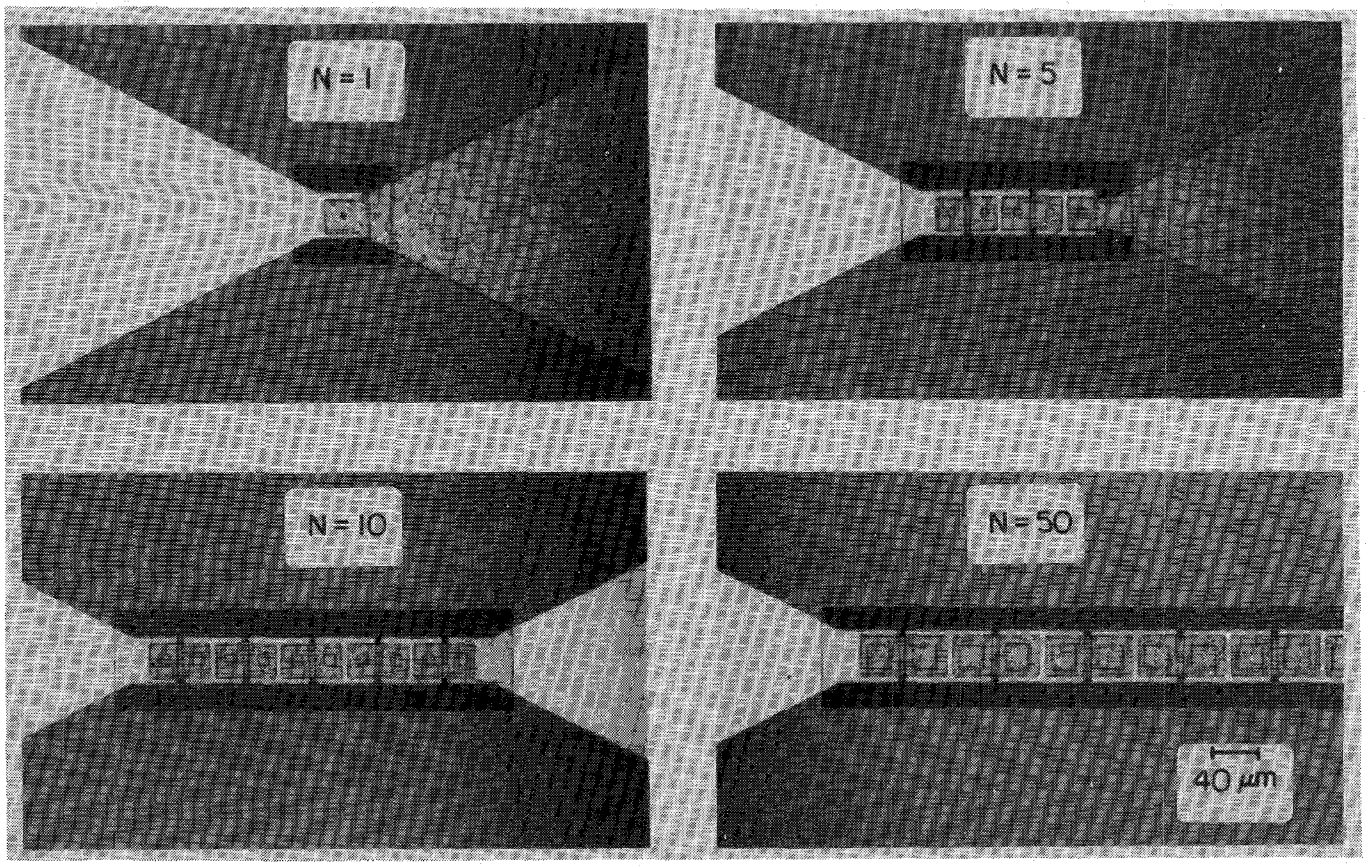

Fig. 2. Optical photographs of series arrays of $N=1$, 5, 10, and 50 SIS tunnel junctions produced by a photoresist liftoff process on a Si substrate. The first layer, of a Pb–In–Au alloy, is called the base electrode. It is patterned to form smooth light triangles at the left of each picture and also at the right for $N=10$. In addition, the base electrode forms a series of smooth light rectangles for $N>1$. The large dark rectangles are a layer of SiO on top of the base electrode. Windows, or holes, in the SiO define the areas of the tunnel junctions, which vary from 6.3 μm^2 for $N=1$ to 324 μm^2 for $N=50$. These windows appear as the smallest squares in each picture. The tunnel currents flow perpendicular to the plane of the paper through the windows and through tunneling barriers that are made by sputter oxidation of the base electrode. The third layer, of a Pb–Bi alloy, is called the counter electrode. It shows as granular triangles at the right for $N=1$ and $N=5$ and also as a series of small rectangles which connect alternate pairs of junctions for $N>1$. The general direction of current flow is horizontal. The current flow in the junctions is alternately into and out of the page.

N. Arguments have been advanced that zero-point noise in array mixers should also be independent of N [5], [11].

III. Fabrication of the Arrays

All of the arrays tested were fabricated at NBS Boulder using a 200-nm Pb–In–Au base electrode on a Si substrate, RF plasma oxidation, and a 430-nm Pb–Bi counter electrode [18]. Junction areas were defined by a window in a 300-nm-thick SiO layer located between the electrodes. The first mixer measurements [12] began with mask set A, which produced arrays of 1, 10, and 50 junctions on one wafer. The junction area, scaled in proportion to N, was 225 μm^2 for $N=50$. Later measurements used mask set B, which produced arrays of 1, 5, 10, 25, and 50 junctions with a junction area equal to 324 μm^2 for $N=50$. An optical photograph of four arrays produced using mask B is shown in Fig. 2.

We observed that the noise temperature of SIS array mixers depends critically on the parameter $\omega_S R_N C$. Values of this parameter were deduced from the Josephson critical current density using specific capacitance data for 13-percent In published by Magerlein [19]. Junction areas were determined on the $N=50$ arrays in order to minimize edge effects. The areas measured from scanning electron micrographs agreed with the nominal mask areas to the accuracy of the measurement. The Josephson critical current was computed, using the relation $I_c = \simeq 0.7\Delta I$ [20], from the current rise ΔI which occurs near the gap voltage $2N\Delta/e$ for unpumped junctions. Since the I–V curve is not perfectly sharp, the procedure used to determine the magnitude of the current rise is somewhat arbitrary. We have chosen to fit one straight line to the I–V curve at the inflection point near the center of the current rise, where the curvature changes sign, and another above the gap voltage. The value of dc current at which these lines intersect was taken to be the current rise. A small correction was made to ΔI due to subgap leakage current.

Since the I–V curves were similar for all wafers, relative values of $\omega_S R_N C$ determined by this technique should be accurate to ± 20 percent. Absolute values, however, may contain additional errors which have a similar effect on the data for all wafers. Mixer data were obtained on four wafers: wafer 1 used mask set A and had $\omega_S R_N C = 2.6$;

wafers 2 through 4 used mask set B and had $\omega_S R_N C = 2.8$, 3.2, and 13, respectively.

IV. Measurement Method

Accurate measurements of mixer noise and gain were required to properly evaluate array performance. The methods used for the early measurements on junctions from mask set A have been reported elsewhere [4]. Arrays from mask set B were measured using a more accurate method [13], which will be described briefly here. The mixer block is a full-height waveguide used in the TE_{10} mode with an adjustable backshort and a screw tuner located $3\lambda_g/4$ in front of the array. Scaled model experiments [21] showed that this mixer block can provide a very wide range of RF source impedances to the array in an RF bandwidth of ~100 MHz. The backshort and screw tuner were adjusted in each experiment to maximize the IF output power resulting from a monochromatic signal at the mixer input. The optimum RF source impedance was generally more capacitive for the longer arrays to compensate for the inductance of the arrays. We believe that optimum coupling was obtained for all mixers tested.

The LO power and monochromatic signal power were coupled to the mixer input through a cold cross-guide coupler, which also served to reduce room-temperature noise. A coupling ratio of 30 dB was used for arrays with $N = 1$, 5, and 10. Only 20 dB could be used for arrays with $N = 25$ and 50 which required more LO power. A specially designed variable-temperature RF load [22] that operated from 1.3 to ~50 K was attached to the straight-through port of the cross-guide to supply a calibrated RF signal power P_1.

The IF output of the mixer passed through a conventional RF choke filter and a transformer designed to provide a resistive 50-Ω IF load. A cooled coaxial switch was used to compare the output power P_o from this transformer with the output power P_2 of a specially designed variable-temperature IF load [22]. Following the switch, the IF train included a bidirectional coupler for IF reflection measurements, two cooled isolators, and a cooled L-band IF amplifier. The noise temperature of the IF system was $T_{IF} \simeq 14$ K.

Measurements were made by selecting an RF load temperature to give a value of P_1. The temperature of the IF load was then varied until the IF load power P_2 equaled the mixer output power P_o. The linear relationship between values of P_1 and P_2 obtained in this way gives the mixer gain and noise temperature [13]. Because of the low temperatures used, it was necessary to use the Planck relation,

$$P = \frac{\hbar\omega B}{e^{\hbar\omega/kT} - 1} \tag{5}$$

to relate radiated power in a bandwidth B to the load temperature T. Reflection measurements were then used to evaluate the IF mismatch, and corrections were made to obtain values of available gain. Using this system, it is possible to measure mixer noise temperatures with an accuracy better than ±2 K and mixer gain to ±8 percent.

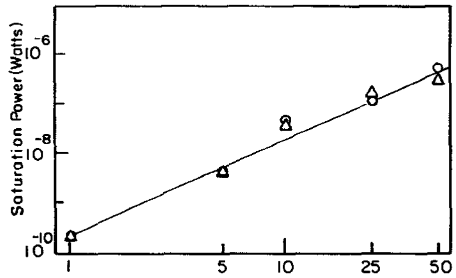

Fig. 3. Power at mixer input that causes 5-percent gain compression for arrays with $\omega_S R_N C = 13$ versus the number N of junctions in series. Open circles give measured powers; triangles give powers after correcting for small gain variations. These data show the expected N^2 dependence. The errors in these measurements are estimated to be comparable to the height of the symbols.

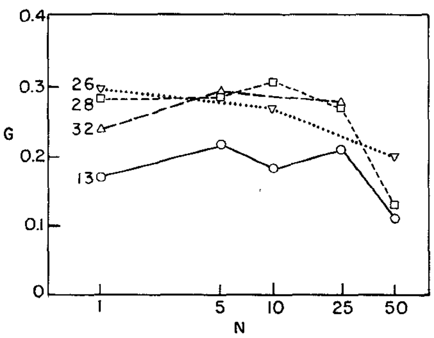

Fig. 4. Available mixer gain G as a function of the number N of junctions in the array. Each curve is labeled with the corresponding value of $\omega_S R_N C$. Typical estimated errors in G are ±0.07, ±0.02, ±0.006, and ±0.01 for $\omega_S R_N C = 2.6$, 2.8, 3.2, and 13, respectively.

These measurements are effectively single sideband since the IF of 1.5 GHz was many times the RF coupling bandwidth. The image sideband was strongly mismatched.

V. Experimental Results

Measurements of mixer saturation were made on arrays from wafers 1, 3, and 4. The circles in Fig. 3 show the monochromatic input power in the upper sideband at 36 GHz required to cause 5-percent gain compression plotted versus N for wafer 4 with $\omega_S R_N C = 13$. It has been suggested [5] that saturation occurs at the mixer's IF output port first; thus, the input saturation power is inversely proportional to mixer gain. The triangles in Fig. 3 represent the data after corrections were made for the small gain variations (see Fig. 4). the slope of these points in the log–log plot is 1.9±0.2, which is in excellent agreement with the expected theoretical dependence on N^2.

Arrays of each length were tested from all four wafers. A magnetic field was required to suppress Josephson instabilities, which occurred at low bias voltages in the arrays with large N. Measurements of the gain of optimized mixers, as shown in Fig. 4, were made using the variable-temperature loads and then checked using monochromatic signals. The results were consistent to better than 20 percent because of the strong image rejection. Some of the data points of Fig. 4 are the average of several measurements of the available mixer gain. Occasional arrays showed poor performance and the data were not included. Up to

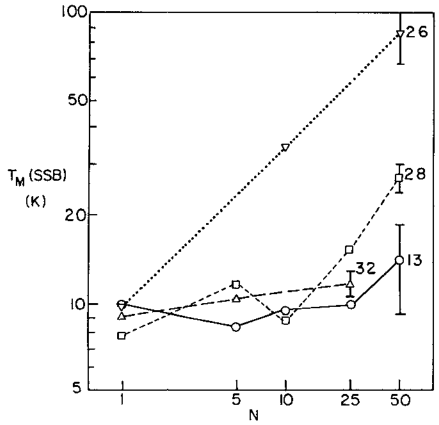

Fig. 5. Single sideband mixer input noise temperature T_M(SSB) as a function of the number N of junctions in the array. Each curve is labeled with the corresponding value of $\omega_S R_N C$. The separation of the curves for large N is much larger than the estimated errors. For clarity, the error estimates are shown only for the points for the largest values of N.

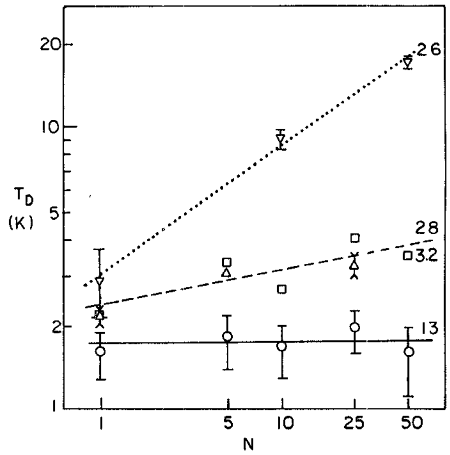

Fig. 6. Mixer output noise temperature T_D as a function of the number N of junctions in the array. Each curve is labeled by the corresponding value of $\omega_S R_N C$. The good fit of the data to straight lines indicates that T_D varies as N^P. Values of P for $\omega_S R_N C = 2.6, 2.8, 3.2$, and 13 are 0.5, 0.1, 0.1, and 0.0, respectively. Estimated errors are shown for those points where they exceed the height of the symbol used to designate the point.

$N = 25$, the gain is essentially constant, as is expected from theory for all values of $\omega_S R_N C$. The gain is significantly lower for $N = 50$. We speculate that the phase of the RF currents may not be constant for these arrays whose length is half the waveguide height.

Measured values of single sideband mixer noise temperature T_M are plotted in Fig. 5 for arrays from all four wafers. There is a trend to increasing values of T_M for large values of N. This trend is most pronounced for arrays with small values of $\omega_S R_N C$. For wafer 4, with $\omega_S R_N C = 13$, T_M is essentially independent of N for $N \leqslant 25$. Since T_M is computed by measuring the noise temperature T_D of the mixer output and then dividing by the measured G, the increase in T_M for $N = 50$ is correlated with the low value of G for that array.

Additional insight into the dependence on N of the noise in arrays can be obtained by plotting the mixer output noise temperature T_D as a function of N, as is shown in Fig. 6. The systematic increase of T_D with increasing N and decreasing $\omega_S R_N C$, which was partly masked by gain variations in Fig. 5, then becomes very clear.

It is possible to speculate about the source of the extra noise seen in arrays with small $\omega_S R_N C$. Since the embedding impedance at the signal frequency required for matching varies systematically with array length, it is likely that embedding impedances at the harmonic and image frequencies also vary. Scaled model measurements [21] showed, however, that the harmonic impedances are so sensitive to the positions of the backshort and screw tuner that these effects are more likely to appear as run-to-run variations in mixer performance than as a systematic increase of mixer noise with array length. Also, calculations based on quantum mixer theory suggest that the mixer noise should not be sensitive to the image impedance for the range of values given by scaled modeling for these experiments.

If the embedding impedances are not responsible for the extra noise, then other mechanisms must be considered. The assumption made in Section II that noise in separate junctions is uncorrelated has little real justification. Effects which can cause correlations, such as injection of nonequilibrium quasiparticles or phase locking of ac Josephson currents [23], are well known and have been studied extensively. It is not known, however, to what extent these or other correlations actually contribute to noise in SIS quasiparticle mixers.

VI. Summary

We have made a systematic study of array mixer performance. In general, mixer gain was independent of N, except for the longest arrays, for all values of $\omega_S R_N C$ tested. The mixer noise was found to increase systematically with increasing N and decreasing $\omega_S R_N C$. This correlation suggests that the response time parameter $\omega_S R_N C$ is important in determining the noise in arrays. Only arrays with $\omega_S R_N C \simeq 13$ showed no significant dependence of noise on N. The saturation power was found to increase as N^2. Thus, the use of arrays with large values of $\omega_S R_N C$ can increase the dynamic range of SIS quasiparticle heterodyne receivers by factors as large as 10^3.

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References

[1] D. W. Face, D. E. Prober, W. R. McGrath, and P. L. Richards, "High quality tantalum superconducting tunnel junctions for microwave mixing in the quantum limit," *Appl. Phys. Lett.*, vol. 48, pp. 1098–1100, 1986.

[2] S.-K. Pan, M. J. Feldman, A. R. Kerr, and P. Timbie, "Low noise 115 GHz receiver using superconducting tunnel junctions," *Appl. Phys. Lett.*, vol. 43, pp. 786–788, 1983.

[3] J. R. Tucker, "Predicted conversion gain in superconductor–insulator–superconductor quasiparticle mixers," *Appl. Phys. Lett.*, vol. 36, pp. 477–479, 1980.

[4] W. R. McGrath *et al.*, "Large gain, negative resistance and oscillations in superconducting quasiparticle heterodyne mixers," *Appl. Phys. Lett.*, vol. 39, pp. 655–658, 1981.

[5] A. D. Smith and P. L. Richards, "Analytic solutions to three-port SIS quantum mixer theory," *J. Appl. Phys.*, vol. 53, pp. 3608–3612, 1982.

[6] L. R. D'Addario, "An SIS mixer for 90–120 GHz with gain and wide bandwidth," *Int. J. Infrared and Millimeter Waves*, vol. 5, pp. 1419–1441, 1984.

[7] P. T. Parrish and R. Y. Chiao, "Amplification of microwaves by superconducting microbridges in a four-wave parametric mode," *Appl. Phys. Lett.*, vol. 25, pp. 627–629, 1974.

[8] P. L. Richards, T.-M. Shen, R. E. Harris, and F. L. Lloyd, "Quasiparticle heterodyne mixing in SIS tunnel junctions," *Appl. Phys. Lett.*, vol. 34, pp. 345–347, 1979.

[9] S. Rudner and T. Claeson, "Arrays of superconducting tunnel junctions as low-noise 10 GHz mixers," *Appl. Phys. Lett.*, vol. 34, pp. 711–713, May 1979.

[10] S. Rudner, M. J. Feldman, E. Kollberg, and T. Claeson, "The antenna-coupled SIS quasiparticle array mixer," *IEEE Trans. Magn.*, vol. MAG-17, pp. 690–693, 1981.

[11] M. J. Feldman and S. Rudner, "Mixing with SIS arrays," *Rev. Infrared and Millimeter Waves*, vol. 1, pp. 47–75, 1983.

[12] H. van Kempen *et al.*, "Conversion efficiency and noise measurements of SIS mixers," in *Proc. 6th Int. Conf. Infrared and Millimeter Waves* (Miami, FL), Dec. 1981, paper M-3-4.

[13] W. R. McGrath, A. V. Räisänen, P. L. Richards, R. E. Harris, and F. L. Lloyd, "Accurate noise measurements of superconducting quasiparticle array mixers," *IEEE Trans. Magn.*, vol. MAG-21, pp. 212–215, Mar. 1985.

[14] R. S. Withers, A. C. Anderson, J. B. Green, and S. A. Reible, "Superconductive delay-line technology and applications," *IEEE Trans. Magn.*, vol. MAG-21, pp. 186–192, Mar. 1985.

[15] S. A. Reible, "Superconductive convolvers with junction ring mixers," *IEEE Trans. Magn.*, vol. MAG-21, pp. 192–196, Mar. 1985.

[16] J. R. Tucker, "The quantum response of nonlinear tunnel junctions as detectors and mixers," *Rev. Infrared and Millimeter Waves*, vol. 1, pp. 1–27, 1983.

[17] J. R. Tucker, "Quantum limited detection in tunnel junction mixers," *IEEE J. Quantum Electron.*, vol. EQ-15, pp. 1234–1258, 1979.

[18] H.-C. W. Huang *et al.*, "High-reliability Pb-alloy Josephson junctions for integrated circuits," *IEEE Trans. Electron Devices*, vol. ED-27, pp. 1979–1987, Oct. 1980.

[19] J. H. Magerlein, "Specific capacitances of Josephson tunnel junctions," *IEEE Trans. Magn.*, vol. MAG-17, pp. 286–289, 1981.

[20] R. E. Harris, R. C. Dynes, and D. M. Ginsberg, "Strong coupling correction to the jump in the quasiparticle current of a superconducting tunnel junction," *Phys. Rev. B*, vol. 14, pp. 993–995, Aug. 1976.

[21] A. V. Räisänen, W. R. McGrath, D. G. Crété, and P. L. Richards, "Scaled model measurements of embedding impedances for SIS waveguide mixers," *Int. J. Infrared and Millimeter Waves*, vol. 6, pp. 1169–1189, 1985.

[22] W. R. McGrath, A. V. Räisänen, and P. L. Richards, "Variable-temperature loads for use in accurate noise measurements of cryogenically-cooled microwave amplifiers and mixers," *Int. J. Infrared and Millimeter Waves*, vol. 7, pp. 543–553, 1986.

[23] A. K. Jains, K. K. Likharev, J. E. Lukens, and J. E. Sauvageau, "Mutual phase locking in junction arrays," *Phys. Rep.*, vol. 109, no. 6, pp. 309–426, July 1984.

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