Superconducting Tunnel Junctions as Mixers at 115 GHz

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Abstract—**Superconducting tunnel junctions have been used as the nonlinear element for mixing at a signal frequency of 115 GHz. The experimental results are compared with predictions of a theoretical analysis based on the quantum theory of mixing of J. R. Tucker. Qualitative agreement is obtained and suggestions are made for quantitative reconciliation. The junctions were small area (~0.4 μm^2) with normal resistances of 60 to 100 Ω and capacitance approximately 20 fF. Measured sensitivity ($T_{MXR}^{SSB} = 62$ K, $L_c = 7.6$ dB) implies receiver noise temperatures superior to the best receivers now in use at this frequency.**

I. Introduction

Recently the promise of low-noise devices using superconducting tunnel junctions has brightened considerably, due largely to spinoff from investment by large laboratories hoping to exploit Josephson junctions for high-speed high-density computers. It was shown by two groups nearly simultaneously [1], [2] that operation as millimeter wave mixers in the photon assisted tunneling regime produces lower noise operation than in the Josephson (pair tunneling) mode previously used. Also, shortly thereafter a series array of superconducting tunnel junctions using normal electron (quasiparticle) tunneling was shown to have low-noise characteristics at 9 GHz [3].

The highest frequency tests to date were by Dolan, Phillips, and Woody [2] at 115 GHz. These were made possible by the fabrication of junctions with small area (~0.4 μm^2) and hence small capacitance with $\omega R_N C \lesssim 1$ at 115 GHz. The value of the capacitance can be extracted from resonant effects in large area junctions and has been determined to be 3.5 $\mu F/cm^2$ by Farris [4]. While the junction capacitance can in principle be tuned out by external circuitry because of the lack of series resistance, bandwidth limitations become severe if $\omega RC \gg 1$, where R is the characteristic impedance of the device. We have used these small-area junctions to obtain improved results at 115 GHz and to compare these results to theoretical predictions.

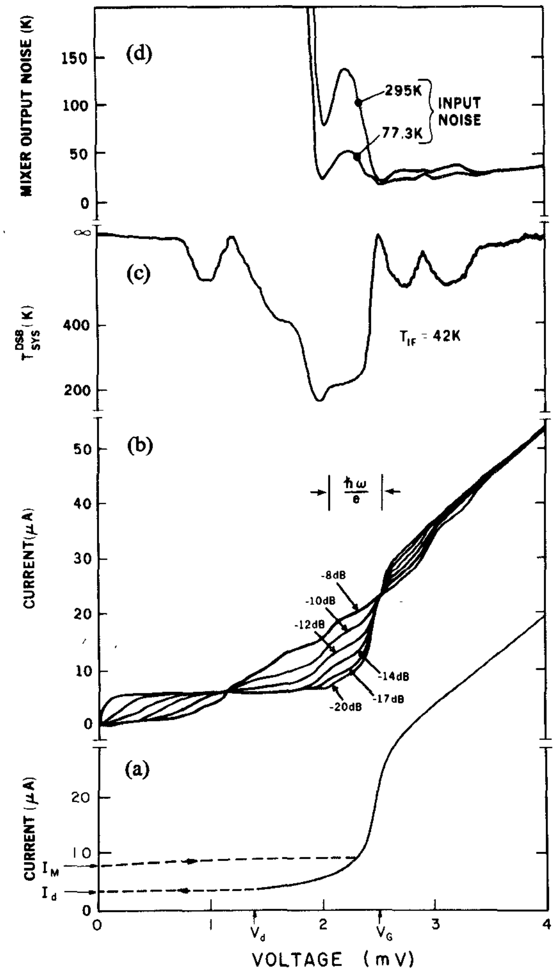

Fig. 1. (a) Measured dc I–V curve without local oscillator power applied. Dashed lines indicate discontinuous transitions. (b) The same junction with local oscillator (115 GHz) power applied showing photon-assisted tunneling steps. (c) Total receiver noise figure as a function of dc bias. (d) Mixer output noise versus dc bias for two different input load temperatures.

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The concept of using quasiparticle tunneling for mixing is attractive because of the strong nonlinearity of the I–V curve near the gap voltage, V_G (see Fig. 1). It was apparent however, that because of the quantum mechanical nature of photon assisted tunneling, classical mixer theory was unlikely to apply. Fortunately a recent theoretical treatment by Tucker [5] has addressed the general problem of a tunnel junction as a circuit element, and it is this formalism we have applied here.

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II. Theory

Beginning with the transfer Hamiltonian of Cohen, Falicov, and Phillips [6], Tucker [5] derives an expression for the time dependence of the quasi-particle current in the presence of a time varying voltage. Pair currents are explicitly excluded from the model. The result for the current can be written in terms of a complex transfer function involving only the dc $I-V$ characteristic and its Kramers–Kronig transform. Thus all properties of the junction are contained in the quasi-particle contribution to the $I-V$ curve, and it will play a central role in the analysis.

The mixer is represented by the usual N-port network [7] and Tucker derives explicit expressions for the mixer admittance matrix. These involve the time dependence of the local oscillator voltage which we assume to be sinusoidal because of the junction capacitance. That is, higher harmonics are assumed shorted. In this case the admittance matrix elements are given as sums of products of Bessel functions and the complex transfer function is evaluated at discrete points separated by $\hbar\omega/e$ in voltage. Shot noise from the local oscillator induced current is calculated in a similar manner.

The results differ strikingly from classical analysis. If the slope of the $I-V$ curve changes significantly over a voltage of $\hbar\omega/e$, reactive mixing terms appear in the admittance matrix which have no classical analog. These will induce parametric effects into the mixer behavior which may be responsible for predicted conversion gain [8].

III. Experiment

Lead alloy junctions similar to those described by Dolan, Phillips, and Woody [2] were fabricated using photolithographic techniques on 0.004-in thick silicon substrates 0.015 in wide by 0.100 in long. An RF choke was incorporated into one of the superconducting leads which served as the bias and IF connections. The substrate was used in a reduced height split block mount fabricated from OFHC copper with the junction centered in the 0.010×0.080-in waveguide opening. Matching of the signal waveguide (0.040×0.080 in) to the reduced height section was accomplished by a single 1/4 wavelength matching section of waveguide of intermediate height, and tuning of the mount was done with a noncontacting backshort similar to that described in Linke, Schneider, and Cho [10]. A cross-sectional view of the mixer block is shown in Fig. 2.

The measurements were made using a low-intermediate frequency (1–2 MHz) defined by low- and high-pass filters. The amplifier used is described in Phillips and Jefferts [11]. It has a very high input impedance and is characterized by a noise resistance of 8 Ω (at 290 K). The effective noise temperature of the amplifier is a function of the junction resistance and for a typical operating point resistance of ~60 Ω, as determined from the $I-V$ characteristics of the junction, the amplifier contributes 40 K at the IF. The dc bias was supplied through a 10 K resistor mounted on the Dewar cold plate. A voltage sense

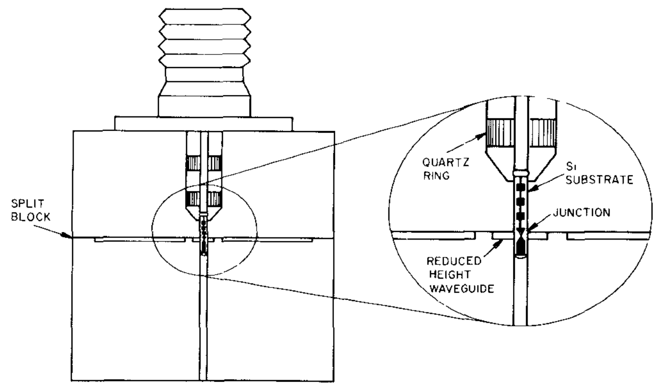

Fig. 2. Cross-sectional view of the mixer block through the plane of the superconducting junction showing the monolithic RF choke on the silicon substrate. An SMA connector is the IF output port.

lead was connected via another cold 10 K resistor and both these leads were attached to low pass filters before leaving the Dewar enclosure. The cold plate was grounded.

A local oscillator signal was obtained from a free-running millimeter wave klystron tuned to 115 GHz and coupled into the signal waveguide through a 20-dB cross-guide coupler. Noise measurements were made with an estimated 10-nW LO power at the mixer. Millimeter wave calibration signals consisted of broad-band noise from free space absorbers at 290 K and 77 K while characterization as a function of bias variables was accomplished using a switched millimeter wave noise tube. These signals were all passed into the Dewar through a 0.002-in thick Mylar vacuum window and coupled to the signal waveguide by a conical feedhorn. The feedhorn, waveguide, and directional coupler were all cooled along with the mixer block to liquid helium temperatures. Loss in the input waveguide and directional coupler were measured at room temperature to be 1.5 dB. The surface resistivity of the silver alloy waveguide changes very little between room and cryogenic temperatures, so corrections were made assuming an input loss of 1.5 dB at a temperature of 4.2 K. The loss of the feedhorn was not known.

The quantities presented in Fig. 1 were all measured as a function of junction bias voltage. Those in Fig. 3 were derived from the measurements of Fig. 1. Junction current (as determined from the voltage across a 10^4-Ω resistor in series with the bias line) is shown in Fig. 1(a) for no local oscillator power. The critical current I_m, drop-back current I_d, gap voltage V_g, and minimum bias voltage V_d are defined in the figure. Dashed lines represent discontinuous transitions. The curves with local oscillator on Fig. 1(b) show clear photon assisted tunneling steps and are discussed further below. Fig. 1(c) is the output of a noise figure meter with switched noise tube input and is a measure of total receiver noise temperature. Fig. 1(d) gives calibrated noise power from the mixer (assuming a constant $T_{IF}=42$ K) for input terminations at 295 and 77.3 K. These curves have been used to calculate conversion loss and effective junction noise temperature T_D as a function of bias (Fig. 3(a) and (b)) using the method described in [9]. We note that the conversion loss variation appears to be mainly responsible for receiver noise

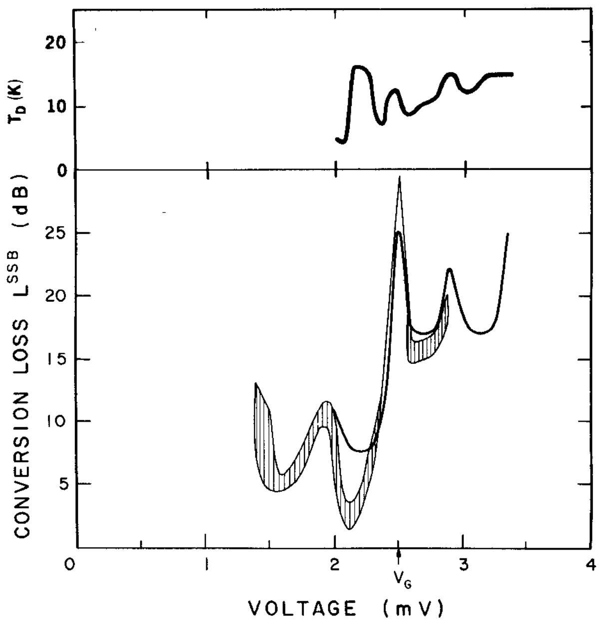

Fig. 3. (a) Single sideband conversion loss versus dc bias voltage. The solid line is the measured conversion loss, the shaded region covers the calculated values for source impedances between 20 and 200 Ω. (b) Effective junction temperature T_D derived from Fig. 1(d).

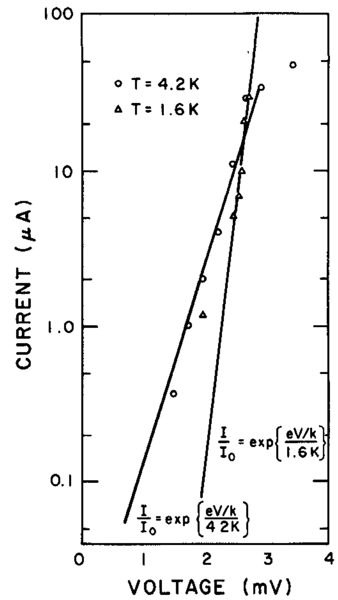

Fig. 4. $I-I_d$ versus V near the gap voltage for two temperatures showing phonon-assisted tunneling.

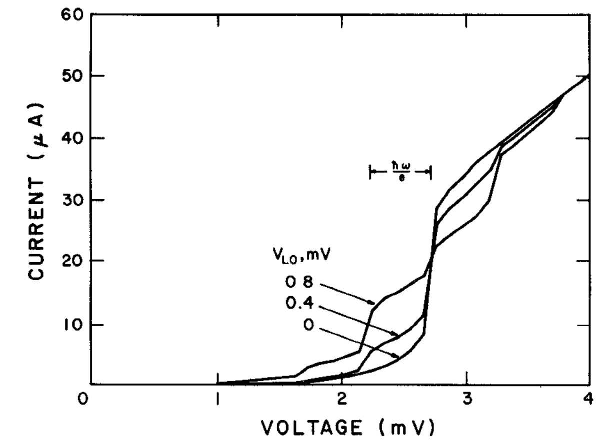

Fig. 5. Calculated dc $I-V$ curves for applied local oscillator voltage amplitude.

temperature variations as shown by the relatively constant T_D. Also shown in Fig. 3(a) is the theoretical conversion loss which will be discussed in the next section.

IV. Analysis

As mentioned in Section II, tunnel junction device parameters are completely determined by the dc quasi-particle $I-V$ curve. Parasitics such as junction capacitance and lead inductance contribute to the embedding network. The experimental $I-V$ curve contains quasi-particle and pair tunneling currents, so a way of separating the quasi-particle contribution must be found. In principle this could be done using a procedure similar to Scott [12] if all the device parameters were accurately known, however sufficient accuracy can be obtained by the fact that the mean pair current is very nearly constant for large bias voltage [12].

The hysteretic $I-V$ curve shown in Fig. 1(a) was obtained with the junction at a physical temperature of 4.2 K. The pair current (and any leakage current) was assumed to be constant ($=I_d$) for voltages above the discontinuous return to $V=0$ at V_d. In Fig. 4 a plot of $I-I_d$ versus V shows exponential behavior, possibly an indication of phonon-assisted tunneling of quasi-particles in lead [13], [14].

In the presence of a photon field of angular frequency ω, the $I-V$ curve acquires steps of width $\Delta V=\hbar\omega/e$ due to photon-assisted tunneling of quasi-particles across the barrier [15]. For an applied voltage $V(t)=V_0+V_1\cos\omega t$, the expression for the $I-V$ curve is [5], [16]

$$I=\sum_{n=-\infty}^{\infty} J_n^2(\alpha)I_{dc}(V_0+n\hbar\omega/e)$$

where $\alpha=eV_1/\hbar\omega$, and the J_n are Bessel functions. This expression has been evaluated for the $I-V$ curve of Fig. 1(a) and is plotted in Fig. 5 for three values of local oscillator voltage V_{LO}. This can be compared to the experimental results in Fig. 1(b). Although Fig. 5 was obtained with constant applied local oscillator *power* and Fig. 1(b) is for constant local oscillator *voltage*, the two are nearly equivalent within $\hbar\omega/e$ of V_G where the junction impedance is nearly constant. We see that the theoretical position of the steps agrees with those observed, and that a computed change of 6 dB in applied power (0.4 mV to 0.8 mV) produces current steps near V_g which correspond to the same relative change of LO power observed in Fig. 1(b). The current responsivity implied by the calculated curves is 1.2 kA/W or about half the quantum limit, $e/\hbar\omega$. To obtain this in practice would require a perfect match to the detector.

Using the formalism discussed in Section II, the performance of the tunnel junction as a mixer can also be predicted. The noise temperature and conversion gain

TABLE I
QUASI-PARTICLE MIXER COMPARED TO 115-GHz COOLED SCHOTTKY BARRIER MIXER SIMILAR TO THAT DESCRIBED IN [10]; ALL VALUES ARE FOR SINGLE SIDEBAND OPERATION; THE NUMBER IN PARENTHESES IS CALCULATED; FOR A DOUBLE SIDEBAND MIXER, $T_{MIXER} = (L-2)T_{DIODE}$

Mixer	Ambient temp (K)	Mixer noise temp (K)	Diode noise temp (K)	Conversion loss (dB)	Receiver noise temp (K) ($T_{IF} = 22$ K)
Quasiparticle	4.2	62	17	7.6	(190)
Schottky barrier	15	240	62	6.9	350

were calculated as a function of dc bias voltage under the following assumptions: 1) harmonics shorted through junction capacitance; 2) intermediate frequency (IF), much less than signal frequency; and 3) reactance tuned out at signal and image, and negligible at the IF. These results are to be compared to the experimental curves in Fig. 3.

In Fig. 3(a) the predicted conversion gain for source impedance between 20 and 200 Ω lies in the shaded region between these two curves. (We note that the predicted loss is at one point below the classical limit of 3 dB. This is a consequence of the quantum treatment of mixing.) The actual source impedance at the junction is difficult to measure, but preliminary scale model work and waveguide obstacle calculations indicate that it lies within this range. The agreement between the calculated and the measured conversion loss is quite good for $V_0 > V_G$, but the observed loss is about 5 dB greater than that predicted below the gap. As this region is the most promising operating point, we have considered various reasons for the discrepancy.

It is possible that the theoretical curve was degraded by some fluctuation of the bias voltage. We considered 60-Hz pickup, local oscillator power fluctuation, and measured $1/f$ noise as possible sources. All these could be eliminated, and the sharpness of the transition at V_G argues against bias voltage smearing. We note that the good agreement for $V_0 > V_G$ rules out some excess loss in the RF or IF circuits since such loss would apply above the gap as well, where we see good agreement. Some effect of pair currents appears quite possible, since these vanish rapidly for $V > V_G$. Unfortunately, it is very difficult to incorporate pair currents into the theory, but they are likely to be large—in our case of the same order of magnitude as the local oscillator current. Saturation is another possible reason for higher measured conversion loss. It is considered unlikely since a 20-GHz bandwidth is required for background radiation to approach 1-percent P_{LO}. Our recent measurements using a coherent source show that saturation is only important for $P_{SIG} > 10$-percent P_{LO}.

Another possible source of the disagreement is that, although greatly attenuated by the junction capacitance, the higher order mixing terms may play an important part as proposed by Shen *et al.* [9]. These harmonics can be included in the admittance matrix in a straightforward way, but their termination is uncertain and the local oscillator voltage waveform is no longer sinusoidal but must be found in a rather elaborate self-consistent calculation [17], [18]. Perhaps this further sophistication will be necessary for future low capacitance junctions.

The theoretically predicted mixer noise temperature is nearly constant at all bias points below V_G and is approximately 5 K. We have considered only shot noise from electrons traversing the barrier. Other noise sources will be investigated in future work. The very rapid increase in noise observed below 2 mV shown in Fig. 1(d) is believed to be caused by local oscillator induced excursions into the unstable region below V_d. Larger junction capacitance would reduce V_d and perhaps increase the region of stable operation.

V. CONCLUSIONS

The superconducting tunnel junction mixer performance is summarized in Table I and compared to the best Schottky barrier mixers presently in use at 115 GHz. The very low mixer noise of the tunnel junction is expected to provide a 200 K receiver noise temperature even with the rather low conversion efficiencies obtained so far. Improvements in IF amplifiers could substantially reduce this receiver noise temperature which is already better than any operating system at present.

Large improvement in the performance of SIS mixers seems to be theoretically possible. *Increasing* the barrier capacitance would, according to our models, reduce the bandwidth thus decreasing the effects of any saturation as well as shunting pair currents and higher harmonics more effectively. The possible beneficial effect on noise has been mentioned in the last section. Series arrays of high capacitance and low impedance junctions could improve the bandwidth and increase the saturation power. Although the theory of Tucker has not yet been generalized to arrays, it is likely that at least the classically predicted conversion loss should be attainable with low mixer noise.

The effect of pair currents on quasiparticle mixing is not understood. It is hoped that theoretical attempts will be made to improve this situation. Experimental approaches being considered are variation of the *RC* product to shunt pair currents, magnetic field suppression of pair currents, and fabrication of superconductor insulator–normal metal junction to eliminate them.

In summary, we have shown that superconducting tunnel junction mixers can be used as low noise mixing elements at 115 GHz with performance superior to present Schottky-barrier systems. Further development should improve this performance toward quantum limits. Higher frequencies also appear to be accessible to this promising device.

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Mode Analysis in Multimode Waveguides Using Voltage Traveling Wave Ratios

DAVID S. STONE

***Abstract*—The voltage traveling wave ratio (VTWR) equations are discussed in general and the specific case of guided traveling waves in multimode circular waveguides is addressed in detail. An experimental technique for measuring VTWR's is described and sample experimental results are analyzed. Measurements of the VTWR's can be easily related to the fractions of total power propagating in each waveguide mode. This information may be used, for example, to examine the mode conversion properties of multimode waveguide components.**

I. INTRODUCTION

MULTIMODE transmission lines, with their virtue of very low insertion loss, have been considered by many authors for long distance communications applications [1]. Recent advances in high average power millimeter wave sources, such as the gyrotron [2]–[4], have revived interest in the study of multimode waveguides to handle power densities which would be prohibitively high in single mode systems.

The ratio of the maximum and minimum values of the beating wave electric fields of any two modes propagating in a multimode guide may, by analogy to the well-established vernacular of the single mode waveguide, be denoted the voltage traveling wave ratio (VTWR) for the two modes in question. In general, the VTWR's will be a function of position in the plane normal to the direction of propagation in the guide. Measurements of the VTWR's can be easily related to the mode power, or the fractions of total power propagating in each waveguide mode. This information may be used to: 1) characterize the operating mode output of a high power source with multimode output such as a gyrotron; 2) analyze the mode conversion properties of overmoded waveguide components; 3) determine the optimum locations along the line for lossy obstructions; and 4) allow impedance matching (induced destructive interference of one or more unwanted modes) [5].

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