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[16] Since at high frequencies $\Omega \gtrsim 1$, the voltage source model is again a good approximation for a point contact obeying the familiar RSJ model, the results of the calculations originally developed for voltage-biased tunnel junctions may be used to investigate the influence of a driving noise current. Therefore, in this situation ($\Omega \gtrsim 1$) the only problem to be solved concerns the physical origin of the internal noise in the junction.

[17] *Note added in proof:* In a recent paper under publication, Tinkham *et al.* have investigated the heating effects in metallic Josephson devices which lead to a noise temperature increasing linearly with the applied voltage (or frequency) at very high frequencies. Therefore, the thermal noise model also gives in these conditions a linear increase of the Josephson linewidth with voltage. However, for a frequency of 1 THz, an estimation of these heating effects for our contacts seems to indicate that they should still be quite negligible.

Results, Potentials, and Limitations of Josephson-Mixer Receivers at Millimeter and Long Submillimeter Wavelengths

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***Abstract*—Millimeter-wave mixers using Josephson point contacts are described, which exhibit a conversion loss $L_c = 9.5$ dB and a noise temperature $T \sim 223$ K for $\lambda \geq 0.95$ mm. Their potentials and limitations in noise, bandwidth, drive power, and stability for receiver applications are discussed.**

I. Introduction

Millimeter-wave mixers using Josephson point contacts have been found to exhibit very low noise. Using these devices noise temperatures of less than 100 K have been measured for frequencies up to about 100 GHz [1]–[3]. No quantitative data are available for the middle and upper millimeter-wave as well as the submillimeter-wave range, where these devices are particularly attractive because of their low intrinsic noise, their wide bandwidth, and their low local-oscillator (LO) power requirements. We report here on a Josephson-mixer receiver which is tunable over the entire 220–325-GHz waveguide band ($0.92 < \lambda < 1.36$ mm), a frequency region where component fabrication difficulties become extremely severe due to small size (e.g., internal waveguide dimensions of 0.43×0.86 mm). Based on these results, potentials and limitations for receiver applications up to 600 GHz are discussed.

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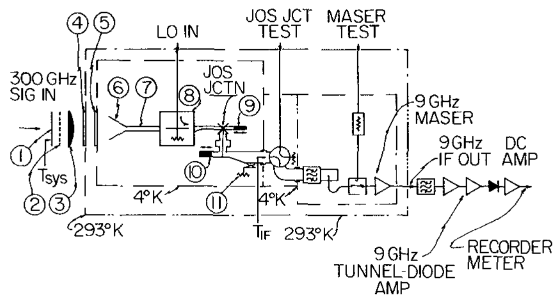

Fig. 1. Block diagram of 300-GHz Josephson-mixer receiver. Component numbers refer to Table I.

II. Description of an Experimental Josephson-Mixer Receiver for $\lambda \sim 1$ mm

A block diagram of a system designed for use as a spectral-line receiver on a millimeter-wave antenna is shown in Fig. 1. The beam of the 300-GHz signal, which is high-pass filtered by means of a screen filter, enters the stainless-steel liquid-helium Dewar through two windows and is focused by a dielectric lens into a scalar horn. The LO signal is injected via a special integrated cross-guide coupler. Following that is the Josephson mixer with a

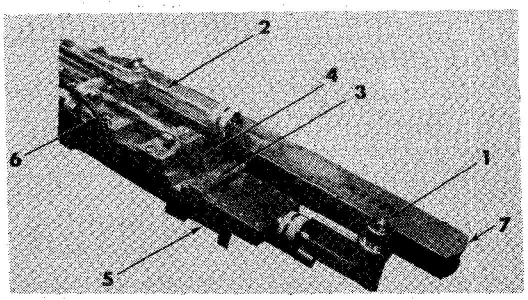

Fig. 2. Josephson-mixer mount of 300-GHz receiver. 1—Scalar horn; 2—LO line; 3—LO cross-guide coupler; 4—*RG* 139 movable signal short lever; 5—Josephson point-contact adjustment rod; 6—Bias cable; 7—*X*-band slip-fit waveguide leading to maser tank.

niobium point contact, a movable back-short, an intermediate frequency (IF) bypass and an adjustable *X*-band IF short. The photograph in Fig. 2 shows the Josephson-mixer mount starting with the 300-GHz scalar horn, 1 , and ending at the *X*-band waveguide, 7 , which leads to the low-noise IF amplifier, an *X*-band maser [4].

One side of the Josephson point contact consists of a 0.75-mm-thick niobium post with a bent and welded whisker of 0.15-mm length and 50-μm diameter. This whisker extends across the reduced-height waveguide (0.15 × 0.86 mm); its end is chemically sharpened to a tip radius of about 1 μm. The other side of the point contact consists of an insulated 0.13-mm-diam niobium wire which is flattened at one end to form the contact anvil. This wire serves as the adjustable member of the junction as well as a coaxial line linking the IF *X*-band waveguide with the 300-GHz guide. A radial choke in this coaxial line prevents loss of the 300-GHz signal into the IF circuitry.

III. DC and RF Bias of the Josephson Junctions

Nonhysteretic Josephson point-contact junctions which exhibited a normal state resistance $R_N \sim 30\ \Omega$ and a supercurrent $I_c \sim 25\ \mu$A, yielded the best mixing results. The product $I_cR_N = 750\ \mu$V for these junctions amounts to about one third of the theoretically possible value of $\pi\Delta/2e$, where $2\Delta/e$, the superconducting gap voltage, is 2.8 mV for niobium. The lowest conversion loss was found to occur at a supercurrent depression of only a few percent referring to an LO drive level of less than 10 μW. (Fig. 3). Experimental evidence at lower frequencies [5], as well as simplified theories [1], suggest that the optimum LO level results in a supercurrent depression of 50 percent. The reason for our lower value is not fully understood. The optimum dc bias point was found to be near 50 percent of the first-step voltage consistent with earlier results [1].

IV. Noise of the Josephson Receiver and Device Contributions

The noise of the system shown in the block diagram of Fig. 1 was measured using the hot–cold (300–70 K) method. Despite the unusually small LO level, the relatively low double-sideband noise temperature, $T_{DSB} = 1500$ K, was measured. A noise temperature $T_{IF} = 20$ K was measured at the slip fit ahead of the switch shown in Fig. 1; this

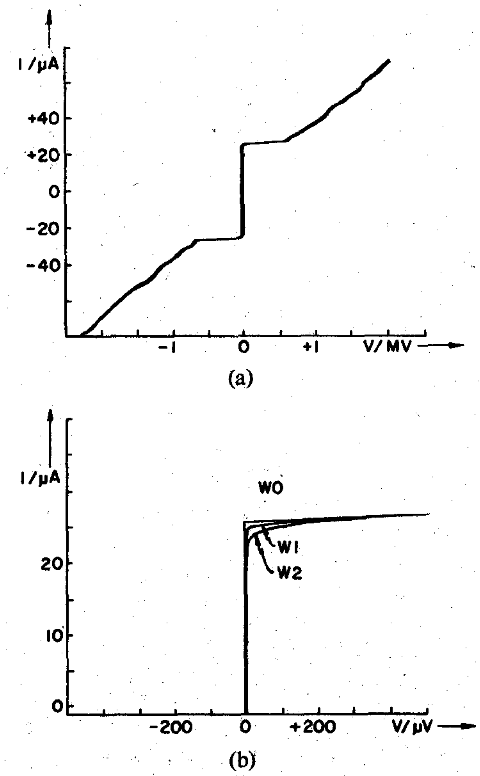

Fig. 3. *I–V* characteristics of Josephson point-contact junction used for 300-GHz mixer. (a) 300-GHz RF biased for optimum system noise as described in Section IV. (b) *W*0—without 300-GHz RF bias; *W*1—with 300-GHz RF bias as in Fig. 3(a); *W*2—with increased 300-GHz RF bias.

includes the contributions of the components shown in the same figure ahead[1] and behind the maser. The maser was set to a gain of 36 dB, yielding a bandwidth of 20 MHz. It is followed by a two-stage tunnel-diode amplifier with a noise temperature $T_{TDA} = 700$ K[2] and a relatively wide bandwidth of 1 GHz. The loss and noise contributions of important components are listed in Table I. The mentioned loss measurements in the 300-GHz range were conducted with the help of a backward oscillator (BWO).

In order to determine the important mixing parameter of the Josephson device, e.g., its single-sideband conversion loss L_c, another experiment was conducted. This test consisted in throwing the coaxial switch ahead of the maser to the "maser-test" port which was terminated by an uncooled load through a 4 K-cooled pad with $L_P = 20$-dB attenuation, as shown in Fig. 1. This produces a well-defined reference noise temperature $T_1 = T_0/L_P + (L_P - 1)(4/L_P) = 7$ K at the input of the maser. The corresponding system output signal A is proportional to $T_1 + T_{IF}'$, where $T_{IF}' = 13.9$ K represents the IF noise temperature at the previously mentioned switch. Another output reading B is obtained in the other switch position when the operating Josephson mixer and the maser are linked while an uncooled absorber ($T_0 = 290$ K) is placed in front of the lens at the system input. This reading B is proportionate to

[1] Loss of waveguide, switches, adapter, and semirigid line: $L = 1.45$ dB.
[2] $T_{TDA} = 900$ K referred to cold output port of maser.

TABLE I
SIGNIFICANT NOISE CONTRIBUTIONS IN THE 300-GHz JOSEPHSON-MIXER RECEIVER

No.$^{\alpha}$	Component Description	Phys. Temp. K	Loss L_R Refl. db	Loss L_D Diss. db	Loss L_T Tot. db	SSB$^{\beta}$ Noise Cont. K
1	Prot. Mylar Film, .075 mm thick	293	0.4	0.25	0.65	474
2	Screen Filter (gold plated 2 mm holes)	293	0.7	0	0.7	489
3	Lens (1 cm Rexolite)	293	0.45	1.5	1.95	1293
4	Vacuum Window (High-Dens. Polyeth.,1.5mm)	293	0.4	0.1	0.5	352
5	Helium Window (1.5 mm Polyethylene)	4	0.4	0.1	0.5	338
6	Corrug. Horn with trans. circ.-rectang. guide & cond. vane	4	2.3	0.2	2.5$^{\gamma}$	1358
7	RG139 Guide between Horn & LO Coupler (5 cm Cu, 5 cm Ag)	4	0	0.15	0.15	106
8	LO Cross Coupler	4	0.14	0.02	0.16	112
9	Movable Red.-Height Waveguide Short	4	1.5	0	1.5	906
10	Movable X-Band Short	4	0.2	0	0.2	66
11	X-Band Coupler, with 4 K Termination	4	0.4	0	0.4	130

Note: α—Component numbers refer to Fig. 1; β—defined as the difference between the system noise temperature with and without one particular component [6]; γ—using 2 horns and 2 lenses a loss of 8 dB per horn and lens was measured at 300 K (including reflections and spillover) which extrapolates to a loss of 4.45 dB for one uncooled lens and one cooled horn.

$(2T_0 + 2T_{DSB})/L_{IN} \cdot L_{OUT} \cdot L_c$, where $L_{IN} = L_{1T} + L_{2T} \cdots L_{9T} = 8.61$ dB represents the measured input loss ahead of the Josephson mixer,[3] $L_{OUT} = 2.05$ dB is the total IF loss ahead of the previously mentioned switch, L_c is the unknown single-sideband conversion loss of the Josephson mixer, and $T_{DSB} = 1500$ K is the measured overall system noise temperature.

The ratio

$$C = \frac{B}{A} = \frac{2T_0 + 2T_{DSB}}{L_{IN}L_cL_{OUT}(T_1 + T_{IF})} \quad (1)$$

was measured to be $C = 1.66$. Using the mentioned values for C, T_0, T_{DSB}, L_{IN}, L_{OUT}, T_1 and T_{IF}', one can obtain from (1) the single-sideband conversion loss $L_c = 9.5$ dB for the Josephson mixer.

Knowing L_c, one can now find the noise temperature T_M of the Josephson mixer from the single-sideband noise temperature

$$T_{SSB} = 2T_{DSB} + T_0 = T_{IN} + L_{IN}T_M + L_{IN}L_cL_{OUT}'T_{IF} \quad (2)$$

of the complete system [6], [7]. The noise term T_{IN}[4] of the input components, is obtained from the equation

$$T_{IN} = (L_{1D} - 1)T_0 + L_{1-2T}(L_{3D} - 1)T_0 + \cdots + L_{1-7T}(L_{8D} - 1)T_4 \quad (3)$$

where $T_0 = 290$ K is again the ambient temperature and $T_4 = 4$ K. This yields $T_{IN} = 198.3$ K using the measured loss values listed in Table I. The loss term $L_{OUT}' = L_{10} + L_{11} = 0.6$ dB in (2) refers to the loss of the two IF components following the mixer (Table I and Fig. 1). Using (2) and (3), and the mentioned values for T_{SSB}, T_{IF}, L_{IN}, and L_{OUT}', a single-sideband noise temperature $T_M = 222.5$ K is calculated for the Josephson mixer. It should be noted that RF and IF mismatch losses are not included in T_M and L_c. They are included in the terms of components 9 and 10 in Table I.

[3] Subscript T denotes total loss, subscript D denotes dissipative loss; the numbers refer to the components of Fig. 1 and Table I.

[4] T_{IN} is not identical with the "SSB noise contribution" of the input components as defined in note β of Table I.

Previous conversion-loss measurements of millimeter-wave Josephson mixers have made use of relatively high-powered klystrons as calibrated signal sources [1], [2]. The method used here to determine the conversion loss L_c of the Josephson mixer has the advantage of eliminating the need for a calibrated single-frequency source at 300 GHz which is very difficult to obtain at this time. It also yields more realistic, and therefore more accurate, values for T_M and L_c since it includes such effects as LO noise [8].

V. DISCUSSION OF NOISE RESULTS AND COMPARISON WITH THEORY

Using simplified theories based on an analog simulator model of the Josephson element [1], [9], a mixer noise temperature [1]

$$T_M = (\beta^2/\alpha^2)T_4 \quad (4)$$

can be calculated. This calculation assumes a relative supercurrent depression $\alpha^2 = 0.04$ and a noise parameter $\beta^2 = 2.36$ for $\Omega = 0.82$ [1]. Using the measured dynamic junction resistance $R_{DYN} = 240\ \Omega$ [Fig. 3(a)] and the mentioned normal state resistance $R_N = 30\ \Omega$, one can then calculate the "net" conversion loss [1]

$$L_c = \frac{R_N}{\alpha^2 R_{DYN}} = 3 \triangleq 4 \text{ dB}. \quad (5)$$

It seems fortuitous that the value predicted by (4) agrees rather well with our measured one. However, an improved analysis of the conversion process, as compared to an earlier short report [10], shows a fairly large disagreement of more than 5 dB between the predicted and the measured L_c values. The following reasons are believed to be responsible for this discrepancy.

a) The stated conversion loss $L_c = 9.5$ dB for the 300-GHz system represents a conservatively high value since the lowest possible noise contributions of some of the components, like the horn and the input waveguide, were used in the evaluation outlined in Section IV.

b) Both the T_M and L_c values undoubtedly contain noise contributions caused by noise sidebands of the LO (BWO). The effects of this FM noise can be deduced from the increased rounding of the zero-voltage steps on the RF-biased I-V curves $W1$ and $W2$ with increasing 300-GHz power [Fig. 3(b)]. Other possible sources of this rounding are: external noise, thermal, and shot noise [8]. It is believed that most of the rounding was due to LO noise. LO noise might also explain the unusually small value of the observed supercurrent depression for optimum noise performance of the system.

VI. Potentials and Limitations

It is of some interest to the systems engineer as well as to the Josephson expert that later tests of the cooled scalar horn used in the 300-GHz receiver revealed an especially lossy vane section. Removal of this section resulted in a reduction of the loss by ~ 1 dB (at 4 K). Although the noise of the system was not remeasured with this change, it is instructive to note that this change, along with the elimination of an unnecessary protective Mylar film and a narrowing of the bandwidth of the tunnel-diode amplifier to 100 MHz, results in an estimated noise temperature (SSB) $T_{sys} = 1320$ K. This latter noise temperature represents a sixfold improvement over the best uncooled mixer receivers [12]; it is comparable to the noise performance of helium-cooled InSb electron bolometers which, however, are limited to a very narrow IF bandwidth ($B \leq 2$ MHz) [13]. Use of a low-noise LO such as a combination of a klystron and a trippler, is expected to lower the system noise even further.

For frequencies below 600 GHz the relatively small required LO power of less than 10^{-5} W can still be obtained via multiplication from 100 GHz using cooled Schottky-barrier varactors [14], [15]. An LO cross-guide coupler similar to the one used in the described 300-GHz system should be usable up to 600 GHz; this method of LO injection results in good directionality of the LO signal and little loss in the signal line. Based on our experience with the 300-GHz system, it appears quite feasible to use the same waveguide construction together with a simpler, not corrugated, conical horn up to 600 GHz. The bandwidth of such receivers is currently not limited by their RF bandwidth, but rather by the bandwidth of existing low-noise IF masers or paramps to 140 or 600 MHz, respectively. More IF bandwidth could in the future be achieved with the help of Josephson paramps such as the *X*- or *Ka*-band units reported by Chiao [16], [17]. The RF tuning range is limited by the tunability of fundamental-drive oscillators, such as 100-GHz klystrons, to about 15 percent when multipliers are available. Millimeter-wave BWO can be used directly as LO sources when a high-frequency IF is available; this is demonstrated by our 300-GHz work where use of a BWO yielded a relatively low system noise temperature.

Our 300-GHz receiver is currently being equipped with a 140-MHz-wide *C*-band maser, a closed-cycle helium refrigerator, a klystron-driven cooled LO trippler, and a stable, permanent Josephson junction similar to the ones successfully tested at 47 GHz [3]. This will make the system field usable, and improve its bandwidth and noise temperature.

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