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Heterodyne mixing with Nb tunnel junctions above the gap frequency

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The noise and gain of a heterodyne waveguide mixer employing Nb/Al_2O_3/Nb superconducting tunnel junctions with an on-chip integrated tuning element are measured and analyzed at 680–750 GHz and at 840 GHz. The lowest receiver noise temperatures are 400 K (double side band) at 720 GHz and 1500 K (3000 K including the beam splitter loss) at 840 GHz. We compare data of the pumped $I-V$ curves with the quantum theory of mixing and demonstrate good agreement at frequencies well above the gap frequency.

Heterodyne receivers based on Nb superconducting tunnel junctions are currently the most sensitive receivers for both ground-based and space-borne astronomical and atmospherical observations up to 500 GHz. The need for sensitive receivers at higher frequencies raises the question whether Nb mixers can be used in the THz regime. Nb-based superconductor-insulator-superconductor (SIS) mixers are approaching the limit set by the 2.8 meV energy gap of Nb, corresponding to a gap frequency ($f_{\mathrm{gap}}=2\Delta/h$, Δ =minimum energy of one quasiparticle excitation) of 680 GHz. Above this frequency, part of the incoming radiation energy will be absorbed without participating in the mixing process because the incoming radiation breaks Cooper pairs in the superconducting electrodes. This extra loss will deteriorate the mixer performance. Habbal *et al.*[1] investigated the behavior of superconducting Sn/Pb tunnel junctions at 604 GHz (the gap frequency of Sn/Pb junctions is 480 GHz). They show that the Tien–Gordon theory for photon assisted tunnelling[2] is applicable to Sn/Pb junctions up to 604 GHz radiation, but no mixing experiments were performed. Based on experiments on Al junctions at 75 GHz (gap frequency of Al is 87 GHz) Winkler and Claeson[3] analyzed the use of SIS mixers at frequencies exceeding the gap frequency. Their general conclusion is that SIS mixers can, in principle, be used up to two times the gap frequency. The theoretical work of Danchi and Sutton[4] leads to the same conclusion.

In this work we present the results of a 600–900 GHz Nb waveguide SIS mixer and compare the results with theory. The receiver has a lowest noise temperature of 400 K double side band (DSB) at 720 GHz and 1500 K DSB at 840 GHz. Analysis of these data shows that the major contribution to the noise temperature is caused by the loss in the superconducting impedance transformer. The measurements suggest that, with a low loss coupling structure, the usable frequency range of SIS mixers can be extended up to two times the gap frequency.

The mixer block used is a scaled version of the 345 GHz receiver described by Honingh *et al.*[5] The full height waveguide has dimensions 0.3×0.15 mm and the 45 μm thick fused-quartz substrate, supporting the junctions and rf filter, is placed across the waveguide in a substrate channel of dimensions 0.1×0.1 mm. The waveguide system has one backshort as a tuning element. The signal and LO power are combined by a 15 or 60 μm thick Mylar beam splitter with a transmission of 95% and 64%, respectively. Due to the difficulty of getting enough LO power at 840 GHz, the thicker beam splitter was used at this frequency. The intermediate frequency (IF) power is measured at a center frequency of 1.4 GHz over a bandwidth of 110 MHz. The noise and gain properties of the system are measured by using "Eccosorb" foam at two different temperatures as a calibrated broadband blackbody signal source ("Y-factor" method).

The results reported here are obtained with a single Nb junction with a normal resistance of 16 Ω, a current density of 12 kA/cm^2, an area of 1 μm^2, and a gap voltage of 2.5 mV. The tunnel junctions are fabricated with the use of a process described elsewhere.[6] To optimize the rf coupling the junction is placed at the end of a superconducting impedance transformer. The width and length of the transformer stripline are 10 and 40 μm, respectively. The thickness of the SiO_2 dielectric layer is 250 nm. Measurements with a Michelson interferometer show that the optimum radiation coupling of this transformer is at 720 GHz and that the bandwidth of the system is very large (170 GHz). Because the transformer is made of Nb, it will give rise to increased loss at frequencies above the gap frequency.

Unfortunately, the quality of the junction and the connecting wiring layers is somewhat worse than previously fabricated junctions. The junction has a relatively large subgap current and subharmonic gap structures are observed in the dI/dV versus V curves and the pumped (and unpumped) output power curves at the IF frequency [Fig. 1(b)]. This indicates the existence of small microshorts. The gap of these junctions is 2.7 mV at 2.2 K, corresponding to $f_{\mathrm{gap}}=670$ GHz and 2.5 mV at 4.2 K, giving $f_{\mathrm{gap}}=603$ GHz.

Analysis of the pumped curves shows that the steepness of the current rise near the gap is partly caused by heating effects, already present in the unpumped curves. This heating effect is caused by the power dissipation due to the dc current and further enhanced by incident radiation, as is evident in the shift of the $2\Delta+\hbar\omega/e$ photon step in Figs. 1(b) and 2(b). In an extreme case the current rise near the gap bends backwards. Due to this heating effect, the comparison of the pumped curves with theory is more difficult, especially near and above the gap voltage. Because the pumped curve con-

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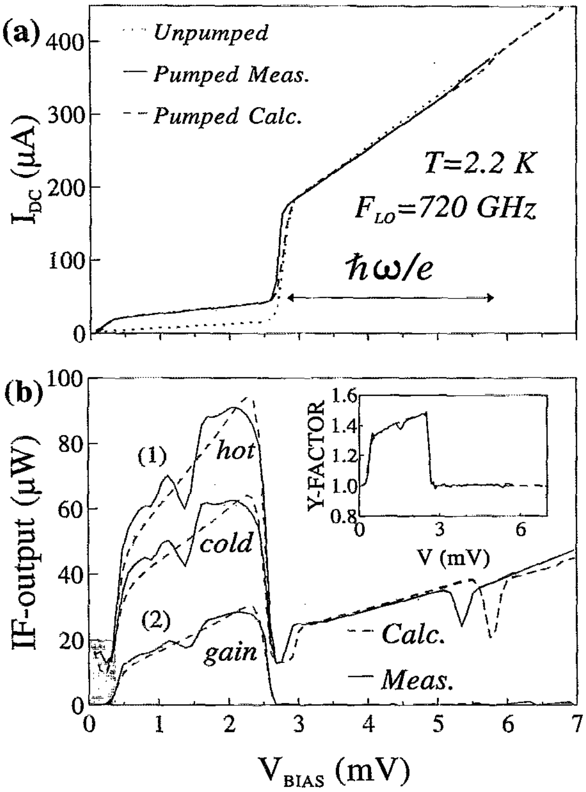

FIG. 1. (a) Pumped, unpumped, and calculated $I-V$ curve at 720 GHz and $T=2.2$ K. The arrow indicates the photon step width $\hbar\omega/e$. (b) (1) Experimental and calculated IF-output power with hot and cold input source. The effective input temperature is increased with 45 K (see text). The difference in position of the measured and calculated photon step above the gap clearly shows the decrease in gap voltage due to heating. (2) Measured and calculated difference (~gain) of the curves displayed in (1). The gray region is the bias range where the photon steps overlap and the conversion is very low. The inset of (b) shows the measured and calculated Y-factor (on a linear scale).

sists of the original unpumped curve shifted over multiples of the photon step voltage, the steepness of the onset of the first photon step (at a low dc current) gives information about the shape of the original unpumped curve without heating near the gap voltage. Based on this information, we calculate a corrected unpumped curve without heating effects, shown in Fig. 1(a).

Figures 1(a) and 2(a) show the pumped and corrected unpumped curves at frequencies of 720 and 840 GHz (at 2.2 and 4.2 K, respectively), together with calculated pumped curves, using Werthamer[7] and Tucker[8]. The curves shown are measured with the backshort tuner and LO power optimized for lowest noise performance of the mixer. The agreement between the calculated and the measured curves in the subgap region is good. Discrepancies near and above the gap, due to the heating effect, are clearly visible. Measurements at 720 GHz with a high quality device (with respect to the subgap current and the gap voltage) of a different batch, designed for 490 GHz, in a 490 GHz mixerblock, do not show these discrepancies. We therefore believe that the measured gap suppression observed here is not an intrinsic effect. The apparently small photon step at 840 GHz, caused by the overlap of photon steps from the positive and negative voltage branch, is well described by the theory.

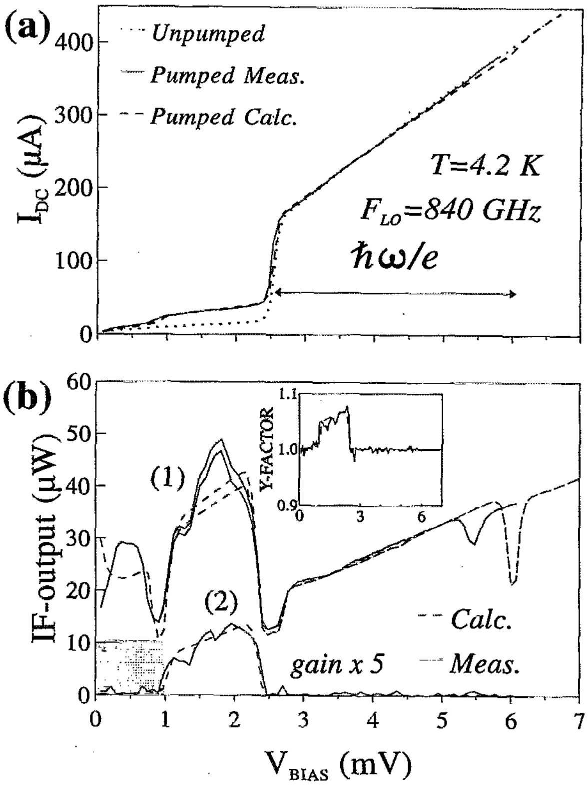

FIG. 2. (a) Pumped, unpumped, and calculated $I-V$ curve at 840 GHz and $T=4.2$ K. The arrow indicates the photon step width $\hbar\omega/e$. (b) (1) Experimental and calculated IF-output power with hot and cold input source. (2) Measured and calculated difference (×5) of the curves displayed in (1). The gray region is the bias range where the photon steps overlap and the conversion is very low [compare with Fig. 1(b)].

The precise shape of the pumped $I-V$ curves depends on the electromagnetic environment (expressed in a conductance g and a susceptance b) seen by the junction. For the embedding parameters at the 720 GHz LO frequency, we derived $g_{\mathrm{LO}}=2$ and $b_{\mathrm{LO}}=0.37$ (normalized to the normal-state conductance). Calculations at 840 GHz give embedding parameters of $g_{\mathrm{LO}}=2.1$ and $b_{\mathrm{LO}}=4.05$. Due to the broadband matching of the superconducting impedance transformer, no clear differences in the upper side band and lower side band embedding parameters are found.

DSB receiver noise temperatures in the 680–750 GHz range are shown in Fig. 3 (for a temperature of 2.2 K). The maximum measured Y-factor $[=P_{\mathrm{out}}(\mathrm{hot})/P_{\mathrm{out}}(\mathrm{cold})]$ is 1.70 dB. In transferring this value to the receiver noise temperatures shown in Fig. 3, the full Planck's law (instead of the Rayleigh–Jeans limit) is used. The measured noise temperatures shown in Fig. 3 constitute the first measurements of Nb SIS mixers at frequencies exceeding the gap frequency.

Although these sensitivities already outperform state of the art Schottky mixers, these numbers themselves do not give direct information about the applicability of Nb SIS mixers up to 1 THz, because the receiver noise temperature includes the noise contributes from the rf-input and the IF-output chain. The total receiver noise temperature, expressed in noise and gain terms of the rf, mixer, and IF components is given by

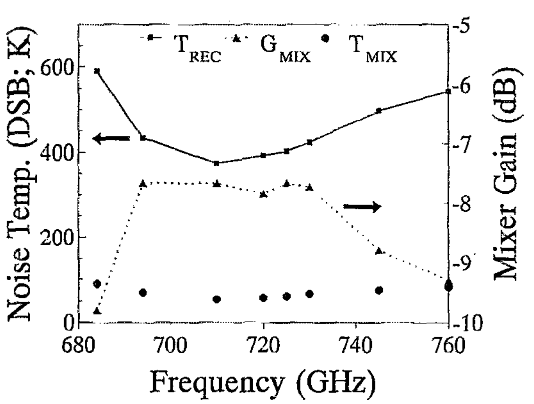

FIG. 3. Tuned DSB noise temperatures of the receiver (solid line) and the mixer (circles). The dashed line is the mixer gain.

$$T_{\mathrm{REC}}=T_{\mathrm{rf}}+T_{\mathrm{MIX}}/G_{\mathrm{rf}}+T_{\mathrm{IF}}/G_{\mathrm{rf}}G_{\mathrm{MIX}}, \tag{1}$$

showing the dependence on both the IF and rf gain and noise contributions.

The gain and noise values for the used IF system, measured by using the unpumped junction as a calibrated noise source at the input of the i.f. chain, are $G_{\mathrm{IF}}=89.1\pm0.1$ dB, $T_{\mathrm{i.f.}}=5\pm0.2$ K. The total gain and noise temperature of the rf input are formed by the beam splitter, the window, the heat filter, the waveguide system, and the superconducting stripline. The loss in the stripline, calculated following Kautz,[9] amounts to a transmission factor of 0.29 at 720 GHz and 2 K, and 0.23 at 840 GHz and 4.2 K. With these numbers, and the noise and loss contributions of the other elements of the rf input, we obtain for the total gain and noise contributions of the rf chain at 720 GHz and 2.2 K $T_{\mathrm{rf}}=42$ K, $G_{\mathrm{rf}}=0.25$. For the 840 GHz measurement, with the thicker beam splitter, a different heat filter, and at 4.2 K, the values are $T_{\mathrm{rf}}=240$ K, $G_{\mathrm{rf}}=0.1$.

With these values of the rf and IF contributions the mixer noise and gain are calculated. Typical values for the mixer gain and noise at frequencies near 720 GHz (shown in Fig. 3) are: $G_{\mathrm{MIX}}=-7.5\pm0.4$ dB, $T_{\mathrm{MIX}}=60\pm20$ K. This value of the measured mixer noise is about 25 K higher than the quantum noise limit at these frequencies ($hf/k\approx35$ K). The mixer noise and gain at 840 GHz are $G_{\mathrm{MIX}}=-13.2\pm0.6$ dB, $T_{\mathrm{MIX}}=145\pm30$ K. As is evident from Eq. (1), the loss in the superconducting stripline has through G_{rf} a major influence on the overall receiver noise performance. By making a coupling scheme with lower loss (e.g., $G_{\mathrm{rf}}=0.5$, which may be realistic for good conducting normal metals), the minimum noise temperature can drop below 250 K at 720 GHz.

The bias voltage dependences of the IF-output power at 720 and 840 GHz are shown in Figs. 1(b) and 2(b). Both figures display the IF output with a hot (293 K) and a cold (77 K) input source. The observed variation at the photon step below the gap is due to the structure in the subgap current. The gain and Y-factor are found by subtraction and division of both IF-output curves. Comparison of the 720 and 840 GHz measurements clearly show that with the increase of frequency, the bias voltage with conversion decreases. At frequencies above $2f_{\mathrm{gap}}$, the bias region of conversion will disappear.

Figures 1(b) and 2(b) also show the IF-output powers, gains, and Y-factors calculated with the quantum theory of mixing. The gain calculations show a very good agreement at 720 GHz. The agreement between the measured and calculated noise and Y-factor is good, but in these calculations the effective input temperature of the hot and cold loads, referred to the junction position (which are only 85 and 30 K due to the loss of the superconducting transformer), is increased by 45 K, of which 17 K is caused by the zero-point fluctuations of the vacuum field. This correction to the noise calculation based on the Tucker theory has also been found in measurements of our group at 345 GHz,[5] but does not appear in our parallel work at 460 GHz.[10,11] It originates in the excess noise due to the subgap current.

The comparison of the calculated IF-output curves with the 840 GHz measurements is reasonably good. The general behavior of the bias voltage dependence of the gain and Y-factor, with no conversion in the overlap region of the two photon steps, is well described, but the calculation of the total IF-output power is less accurate. We contribute this to the relatively large uncertainty in the embedding parameters at 840 GHz. The peaked shape of the IF-output is partly caused by remnants of the ac-Josephson effect, which causes a further discrepancy between the calculations and the measurements.

In conclusion, we have performed mixing measurements with Nb tunnel junctions at frequencies above the superconducting gap frequency. The results are very encouraging and show that Nb tunnel junctions in principle can be used up to 1.4 THz. The loss in the superconducting tuning circuit is considerable and has a major influence on the mixing performance. Operation at THz frequencies will require the use of low resistive materials for the electrodes. The measured data are compared with the quantum theory of mixing and a good agreement of the calculated and measured mixer performance is found.

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