Low-noise 1 THz niobium superconducting tunnel junction mixer with a normal metal tuning circuit

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We describe a 1 THz quasioptical SIS mixer which uses a twin-slot antenna, an antireflection-coated silicon hyperhemispherical lens, Nb/Al-oxide/Nb tunnel junctions, and an aluminum normal-metal tuning circuit in a two-junction configuration. Since the mixer operates substantially above the gap frequency of niobium ($\nu > 2\Delta/h \sim 700$ GHz), a normal metal is used in the tuning circuit in place of niobium to reduce the Ohmic loss. The frequency response of the device was measured using a Fourier transform spectrometer and agrees reasonably well with the theoretical prediction. At 1042 GHz, the uncorrected double-sideband receiver noise temperature is 840 K when the physical temperature of the mixer is 2.5 K. This is the first SIS mixer which outperforms GaAs Schottky diode mixers by a large margin at 1 THz. © *1996 American Institute of Physics.* [S0003-6951(96)00412-1]

Heterodyne mixers based on superconducting tunnel junctions (SIS mixers) are used in the most sensitive receivers for radio astronomy at millimeter and submillimeter wavelengths. The best quasioptical and waveguide mixers use Nb/Al-oxide/Nb junctions with integrated niobium tuning structures, and have achieved noise temperatures within a factor of 10 of the quantum limit ($T_{ql} = h\nu/k_B$ for the single-sideband noise temperature) at frequencies below the Nb gap ($\nu < 700$ GHz).[1] Theoretically, heterodyne mixing in SIS devices is useful up to twice the gap frequency.[2,3] However, the rf loss of superconductors increases significantly above the gap frequency because the rf photons have sufficient energy to break Cooper pairs. This causes a larger fraction of the incoming radiation to be dissipated in the superconducting electrodes and tuning structures, which degrades the mixer performance. Good results have recently been obtained in the 800 GHz band with all-Nb mixers,[4–6] which supports the idea that efficient mixing in SIS junctions is possible above the gap frequency.[7] Nonetheless, the noise temperatures do rise rapidly with frequency above 700 GHz, presumably because of the increasing dissipation in the Nb tuning circuit.

In principle, tuning circuits fabricated using a high conductivity normal metal such as aluminum should offer better performance above 800 GHz.[8,9] This approach has been demonstrated in a 1 THz SIS waveguide mixer by van de Stadt *et al.*,[10] with initial results that are comparable to existing Schottky diode mixers. We have designed, fabricated, and tested a 1 THz quasioptical Nb/Al-oxide/Nb SIS mixer which uses aluminum tuning circuits. The Nb/Al mixer design incorporates a twin-slot antenna, a two-junction configuration, and an antireflection-coated silicon hyperhemispherical lens. The mixer optics, layout, and equivalent circuit are described in detail in our earlier papers[11–13] on all Nb mixers. The resulting uncorrected DSB receiver noise temperature is 840 K at 1042 GHz. This is over a factor of four better than the best reported GaAs Schottky diode mixers at this frequency.[14]

The mixers are designed using a microwave circuit simulation program which we have developed.[9] We calculate the rf coupling efficiency, which is the fraction of the radiation power received by the twin-slot antenna that is absorbed by the tunnel junction. This includes the impedance mismatch between the slot antenna and the microstrip circuit. The frequency dependent complex antenna impedance is obtained from a moment-method electromagnetic calculation.[15] For our Nb/Al mixer design, we optimized the rf coupling in the 1000–1100 GHz band for a junction area of 1.7 μm^2 and a current density of 10 kA cm^{-2}.

The surface impedance losses in the microstrip lines are also included in our calculations of the rf coupling efficiency. In Fig. 1, the power loss per wavelength and the attenuation per unit length for both Nb and Al microstrip lines are plotted as a function of frequency. It can be seen that the loss in Nb microstrip is negligible below the gap frequency, but increases dramatically above 700 GHz. Our calculations show that the losses of the Nb and Al microstrip lines are about equal at 830 GHz. The reason for this behavior is that the surface impedance of Nb approaches that of a normal metal at freqencies far above the gap. The normal-state resistivity of our Nb films just above the critical temperature (9.2 K) is 5 $\mu\Omega$ cm, which is rather high when compared to good normal metals. The resistivity ρ of bulk aluminum at room temperature is 2.45 $\mu\Omega$ cm, which corresponds to an electron mean free path l of 16 nm.[16] At low temperatures, the bulk resistivity can be much smaller. However, the 200 nm thickness of our Al film sets an upper limit on the electron mean free path. Because the product ρl is independent of temperature,[16] the resistivity ratio $\mathscr{R} = \rho(300\ \mathrm{K})/\rho(4\ \mathrm{K})$ is limited to roughly $\mathscr{R} \leqslant 10$. In practice, we measure $\mathscr{R} \approx 5$. Nonetheless, the resistivity of Al films can be an order of

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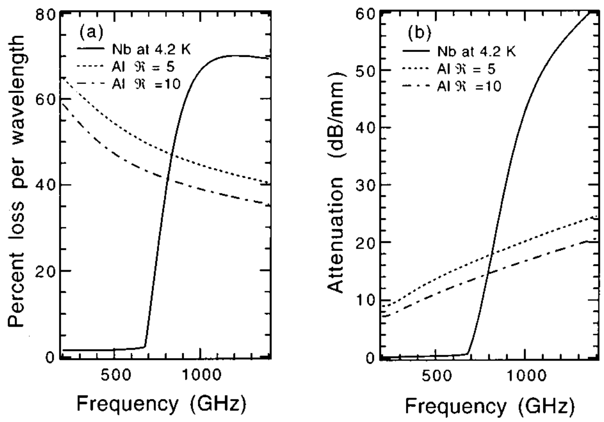

FIG. 1. The calculated frequency dependence of (a) the power loss per wavelength and (b) the attenuation per unit length are plotted for 5 μm wide microstrip lines. The insulation layer is 400 nm SiO and the metal thickness is 200 nm. Calculations are made for temperature at 4.2 K. Two resistivity ratios [$\mathscr{R}=\rho(300\ \mathrm{K})/\rho(4.2\ \mathrm{K})$] 5 and 10 are used for Al film in the calculations whereas the room-temperature resistivity is assumed to be 2.45 $\mu\Omega$ cm.

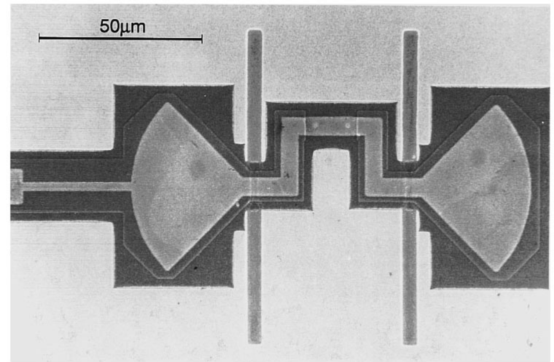

FIG. 2. A SEM picture of the mixer chip. The two vertical slots in the ground plane form the twin-slot antenna. The two small dots at the center of the microstrip line are the SIS junctions.

magnitude lower than that of Nb. Since the film thicknesses (and presumably the electron mean-free paths) are much larger than the classical skin depth, we calculate the surface impedance of the Al films using the theory of the nonlocal anomalous skin effect for finite thickness films.[17] The surface impedance of niobium can be calculated to a good approximation using the Mattis–Bardeen theory in the local limit.[18]

The Nb/Al devices were fabricated on 50 mm diameter, 0.25 mm thickness high-resistivity silicon wafers using a modified Nb/Al-oxide/Nb junction process. First, a 2000 Å aluminum ground plane was deposited, followed *in situ* by the Nb/Al-oxide/Nb trilayer. The ground plane and slot antennas are patterned in this step using a liftoff technique. The junctions are defined with optical lithography and are formed by reactive ion etching (RIE) of the Nb/Al-oxide/Nb trilayer. All of the unprotected Nb must be removed so that the Al ground plane is exposed for the microstrip lines. The junctions are isolated with a 2000 Å SiO film patterned by self-aligned liftoff, and a second 2000 Å SiO film is added to produce a total SiO thickness of 4000 Å for the impedance transformer. The 2000 Å Al wiring layer is deposited as the last step. The SEM photograph in Fig. 2 shows the device.

The measured dc $I-V$ curves have a sloped supercurrent, which is the result of a 2.7 Ω series resistance. This is caused by the resistive current path through the Al wiring. The current path consists of $\approx$106 squares of the 2000 Å thick Al film, which implies a resistivity of 0.51 $\mu\Omega$ cm and a resistance ratio $\mathscr{R}=4.8$. The normal-state resistance is $R_n=12.8\ \Omega$ for each 1.7 $\mu\mathrm{m}^2$ junction.

The receiver optics consists of a 10 or 25 μm thick mylar LO injection beamsplitter, a 25 μm thick mylar vacuum window, a 2.2 mm thick uncoated quartz IR filter at 77 K, a polyethylene lens at 4 K, and an antireflection (AR) coated silicon hyperhemispherical lens. The AR coating on the hyperhemisphere was optimized for 850 GHz and has $\approx$85% transmission at 1042 GHz. The receiver noise temperature was measured using the standard Y-factor method with a hot load at 290 K and a cold load at 80 K, with a 1 GHz (IF) bandwidth.

The direct-detection response of the device was measured using a Fourier transform spectrometer (FTS). This gives the frequency dependence of the rf coupling efficiency. Figure 3 shows a FTS result along with the response predicted by the circuit simulation. Since the optical coupling efficiency is not well known, we scaled the vertical axis of the experimental curve to match the theoretical one. Using a junction capacitance of 85 fF $\mu\mathrm{m}^{-2}$ in the simulations gave a good match to the experimental data. The simulation predicts the shape of the response quite well except at the higher frequencies. The experimental data above 1100 GHz is affected by the strong absorption lines caused by the residual water vapor that is present in our nitrogen-flushed FTS system. Additional nonidealities are the resonant peaks approximately 50 GHz apart caused by Fabry–Perot resonances in the uncoated quartz IR filter.

Local oscillator power at 761.6 and 1042 GHz was generated using a difluoromethane (CH_2F_2) far-infrared laser, pumped by a $\lambda=10\ \mu$m CO_2 laser. Measurements at 800 GHz were obtained using a 133 GHz InP Gunn oscillator followed by a cascaded ($\times2\times3$) GaAs Schottky varactor multiplier. At a bath temperature of 4.2 K, the DSB receiver noise temperatures were 1830, 970, and 1170 K at 761.6, 800, and 1042 GHz, respectively. Our noise temperatures are

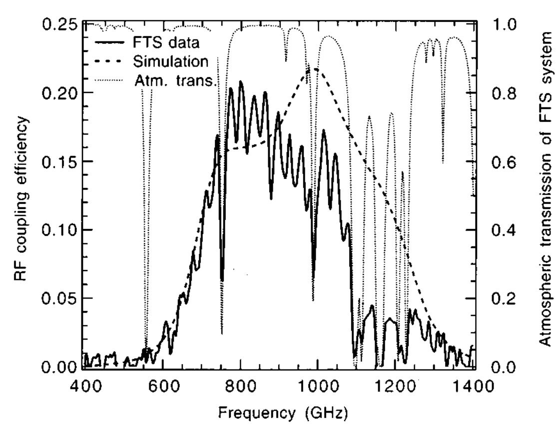

FIG. 3. Direct detection response measured with the FTS. The heavy dashed line is the calculated rf coupling efficiency. The atmospheric transmission is calculated assuming a relative humidity of 13% and a path of 3 m.

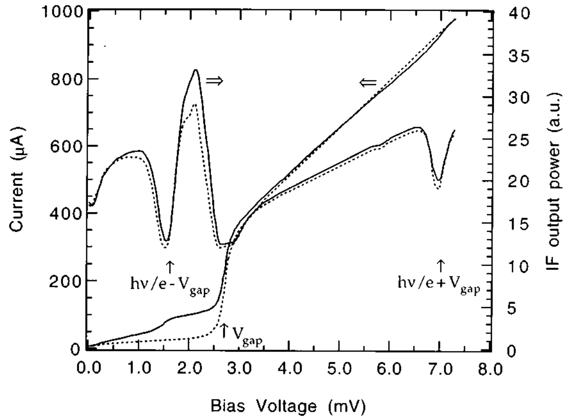

FIG. 4. Heterodyne measurement results at 4.2 K and 1042 GHz. The $I-V$ curve with (solid) and without (dashed) LO pumping are plotted, along with the IF output power when hot (295 K, solid line) and cold (80 K, dashed line) loads are placed at the receiver input. Notice that the dips in the IF power appear at the correct voltages $h\nu/e \pm V_{gap}$.

not corrected for the beamsplitter or other optical losses. The large difference in noise temperatures at 761.6 and 800 GHz is in part due to the Fabry–Perot resonances in the quartz IR filter, which can cause the transmission to vary by 40%. When the mixer was cooled to 2.5 K, the noise temperature dropped to 840 K at 1042 GHz. The 40% improvement in the receiver noise temperature at the lower temperature can be largely explained by the reduction in the subgap leakage current and the increase in the gap voltage. Tucker theory[19] calculations indicate that these effects result in a 20% drop in the mixer noise temperature and a 35% reduction in the conversion loss. Therefore, a 25%–30% reduction in the receiver noise temperature can be expected from these effects. Figure 4 shows the 4.2 K $I-V$ curves with and without 1042 GHz LO power, and the IF power versus bias voltage with hot (290 K) and cold (80 K) loads placed at the receiver input. The bias voltage has been corrected to remove the effect of the Al stripline series resistance. The smooth IF power curve indicates good suppression of the Josephson noise by applied magnetic field. Note that the first Shapiro step occurs at $h\nu/2e \sim 2$ mV, and therefore, suppression of the Josephson noise is critical.

We used the shot-noise technique[20,21] to estimate the IF noise temperature and the receiver conversion loss, which gave $T_{IF} \approx 6$ K and $L_{conv} \approx 16$ dB (DSB). This agrees with independent measurements of the HEMT IF amplifier noise temperature. The total rf signal losses in the receiver, including the optics and the Al microstrip circuit, are estimated to be about 8.2 dB (see Table I). Using Tucker's theory in the 3-port approximation,[19] we calculate that the intrinsic conversion loss of the SIS junction is around 8.3 dB (DSB) at 1040 GHz. The total estimated DSB receiver conversion loss is therefore 16.5 dB, which is in reasonable agreement with the measured value.

In summary, we have designed and fabricated Nb SIS mixers with normal metal Al tuning structures. Heterodyne mixing was performed at 1042 GHz and a double-sideband receiver noise temperature of 840 K was measured at a temperature of 2.5 K. It may be possible to further reduce the receiver noise by optimizing the optical components. Our work demonstrates that Nb junctions can offer superior performance at THz frequencies when implemented with low-loss normal-metal Al tuning structures.

TABLE I. Estimated contributions to receiver conversion loss (DSB).

Component	Estimated loss (dB)	Physical temperature (K)
Beamsplitter (10 μm mylar)	0.2	295
Dewar window (25 μm mylar)	1.0	295
IR quartz filter	0.5	77
Polyethylene lens	0.5	4.2
Silicon lens and antenna	0.7	4.2
Al microstrip circuit	5.3	4.2
Intrinsic junction conversion loss	8.3	⋯
Total conversion loss:	16.5	⋯

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