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We have developed a low-noise 850 GHz superconductor-insulator-superconductor (SIS) quasiparticle mixer with NbTiN thin-film microstrip tuning circuits and hybrid Nb/AlN/NbTiN tunnel junctions. The mixer uses a quasioptical configuration with a planar twin-slot antenna feeding a two-junction tuning circuit. At 798 GHz, we measured an uncorrected double-sideband receiver noise temperature of $T_{RX} = 260\,\mathrm{K}$ at 4.2 K bath temperature. This mixer outperforms current Nb SIS mixers by a factor of nearly 2 near 800 GHz. The high gap frequency and low loss at 800 GHz make NbTiN an attractive material with which to fabricate tuning circuits for SIS mixers. NbTiN mixers can potentially operate up to the gap frequency, $2\Delta/h \sim 1.2\,\mathrm{THz}$.

Superconductor-insulator-superconductor (SIS) quasiparticle mixers based on Nb have developed to the point that their sensitivity below the gap frequency of Nb, $2\Delta/h \approx 700\,\mathrm{GHz}$, is nearly quantum-limited.[1] Quantum-limited noise performance of SIS mixers was predicted to be possible 2 decades ago,[2] and the development of SIS mixers has progressed steadily since then.[3,4] In terms of the single sideband noise temperature, the quantum noise limit is $T_N = h\nu/k_B$, or $T_N/\nu \approx 48\,\mathrm{K\,THz^{-1}}$, and SIS receivers have reached within a factor of 10 of this fundamental limit. In modern SIS receivers, only a fraction of the total receiver noise, usually represented by T_{RX}, the receiver noise temperature, actually originates from the mixer itself; rather, the thermal noise from warm optical elements at the input and noise from the intermediate frequency (IF) amplifier are responsible for much of the total receiver noise. Thus, in a real sense, SIS mixer elements perform their function nearly perfectly. This level of performance has been achieved as a result of advances in the fabrication of small-area high current density Nb/AlO$_x$/Nb junctions, as well as improved mixer designs that integrate Nb superconducting tuning circuitry with the junction.

Above 700 GHz, photons have sufficient energy to break Cooper pairs in Nb, causing substantial resistive losses in tuning circuits. To produce SIS mixers for frequencies above 700 GHz, one can use a high conductivity normal metal instead of Nb in the tuning circuits.[5] Through this method, Nb SIS mixers have been extended to 1 THz; however, significant losses in the tuning circuits have prevented them from achieving near-quantum-limited performance. It is noteworthy that despite these losses, Nb SIS mixers are still competitive with other mixer technologies near 1 THz.

Obviously, the use of superconducting materials with gap frequencies higher than that of Nb could possibly push the low-noise operation of SIS mixers above 700 GHz. The best studied material is NbN, which has a gap frequency as high as $2\Delta/h \approx 1.4\,\mathrm{THz}$ in films suitable for use in mixers. However, the reported performance of NbN mixers has been somewhat disappointing: even below 700 GHz the best noise temperatures have been considerably worse than those of Nb mixers.[6–8] Though it is difficult to pinpoint the exact cause of this, two possible fundamental limitations of NbN mixers have been identified. One is excess shot-noise in the junction caused by multiple Andreév reflection (MAR) tunneling in pinhole defects in NbN-based junctions.[9] This could possibly be circumvented if NbN tuning circuits were used with non-NbN junctions. A potentially more serious problem, however, is the high surface resistance of polycrystalline NbN at submillimeter wavelengths.[10] The quality of NbN films is very sensitive to the substrate temperature during deposition, and generally, films of better quality can be grown on heated substrates. However, high current density junctions used in SIS mixers are usually destroyed by the high temperatures necessary for this process. Therefore, in NbN mixers the film used for the wiring layer is usually much poorer in quality compared to the ground plane film. An indication of this fact is that an SIS mixer with NbN ground plane and Al wiring gives about the same noise performance[11] as a Nb mixer with Al wiring.[5] It is thus believed that the losses in the wiring layer film are responsible for the relatively poorer performance of all-NbN mixers.

Another possible material is NbTiN, which has a similarly high T_c, but unlike NbN, high quality, low resistivity films can be deposited at low substrate temperatures. The properties of NbTiN were first investigated at about the same time the first NbN films were being fabricated,[12] and there has been recent work with NbTiN films to evaluate

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their potential use in RF cavities for particle accelerators.[13] Our recent work with mixers using NbTiN films has demonstrated that they can have very low loss at frequencies as high as 800 GHz, and thus may be suitable for use in mixers operating up to the gap frequency $2\Delta/h \approx 1.2$ THz. For instance, a mixer with Nb/AlO$_x$/Nb junctions, Nb wiring, and a NbTiN ground plane gave very impressive performance, $T_{RX} = 110\,\mathrm{K}$ (DSB) at 638 GHz.[14] This result clearly shows that the loss of the NbTiN ground plane near 650 GHz must be at least comparable to that of a Nb ground plane. Fourier transform spectrometer (FTS) characterization of mixers made entirely from NbTiN films with MgO tunnel barriers indicated that the excess surface resistance of the NbTiN films was $R_S < 0.03\,\Omega$ at 500 GHz, and had an upper limit of roughly $R_S < 0.1\,\Omega$ at 800 GHz.[15] These measurements further suggest that NbTiN films have lower loss at submillimeter wavelengths than NbN films. Within the past year considerable improvements have been made in our fabrication process,[16,17] and here we report on measurements made near 800 GHz on a mixer with NbTiN wiring and Nb/AlN/NbTiN junctions.

Our mixer configuration uses a quasioptical planar twin-slot antenna coupled to a two junction tuning circuit.[18] The mixer ground plane and the microstrip wiring are made from NbTiN thin films. The mixer uses sub-micron hybrid Nb/AlN/NbTiN junctions. These are preferred over all-NbTiN junctions (e.g., NbTiN/MgO/NbTiN) since the subgap leakage currents are lower and current-voltage (*I*-*V*) characteristics are sharper. They are also preferred over Nb/AlO$_x$/Nb junctions because of their higher sum gap voltage (3.2 mV vs. 2.9 mV); furthermore, the AlN tunnel barrier introduces the possibility of making junctions with extremely high current densities.[19]

The trilayer fabrication closely follows the process described previously,[16] except for two important modifications. First, we now use a Au interlayer between the NbTiN ground plane and the Nb base electrode of the junction. Our experiments comparing mixers with and without the Au layer indicate that the Au layer may be necessary to ensure a good RF contact between the NbTiN ground plane and the Nb base electrode. The second difference is in the plasma nitridation process for producing the AlN tunnel barrier. Previously, the RF bias for the plasma nitridation was routed through the substrate chuck. By moving the RF electrode to a different position, the system was able to produce high quality junctions with better control and repeatability.

The fabrication of the mixer begins with the deposition of the ground plane, which is a NbTiN film deposited to a thickness of 300 nm on an unheated oxidized Si wafer. The ground plane film has $T_c \approx 15.2\,\mathrm{K}$ and $\rho(20\,\mathrm{K}) \approx 75\,\mu\Omega\,\mathrm{cm}$. A thin (20 nm) blanket layer of Au is evaporated over the ground plane. On top of this, the Nb/AlN/NbTiN trilayer is fabricated. It begins with 150 nm of Nb, followed by 7 nm of Al. The AlN barrier is formed by plasma nitridation. The junction counter-electrode is 50 nm of NbTiN. The tunnel junction has a critical current density of $J_c \approx 10\,\mathrm{kA\,cm^{-1}}$ or $R_N A \approx 20\,\Omega\,\mu\mathrm{m}^2$. The junction has a specific capacitance similar to AlO$_x$ for the same value of the current density.[19,20] The junctions are nominally defined to dimensions of $2.6 \times 0.25\,\mu\mathrm{m}$ using e-beam lithography employing a cross-line process.[21] The junctions are made to stretch across the width of the tuning inductor. This junction geometry is used instead of square junctions to eliminate any spreading inductance, which considerably simplifies the mixer design calculations and reduces the RF loss in the Nb junction base electrode. Finally, after the SiO dielectric for the microstrip transmission lines is laid down, the deposition of 500 nm thick NbTiN for the wiring layer completes the mixer. The NbTiN on SiO has a slightly lower T_c and higher resistivity, $\rho(20\,\mathrm{K}) \approx 100\,\mu\Omega\,\mathrm{cm}$. An SEM image of a completed 850 GHz mixer is shown in Fig. 1.

The receiver setup is nearly identical to that used in our prior measurements of Nb SIS mixers, which gave excellent performance up to 1 THz.[5,22] The SIS mixer chip is glued to a hyperhemispherical Si lens, which is anti-reflection coated with Al$_2$O$_3$-loaded epoxy. The lens/substrate combination is clamped into a copper mixer block assembly, which is mounted to the cold plate of a liquid helium-cooled cryostat. The input beam passes through several layers of porous Teflon on the 77 K radiation shield and a high-density polyethylene lens at 4.2 K. A $25\,\mu\mathrm{m}$ mylar film serves as the vacuum window. The local oscillator (LO) is provided by a Gunn oscillator followed by 2 varactor multiplier stages ($\times 2 \times 3$). The LO is coupled to the signal beam with a $12.5\,\mu\mathrm{m}$ Mylar beam splitter, which is about 92% transmissive near 800 GHz.

The unpumped *I*-*V* curve of the 850 GHz mixer is shown in Fig. 2, which represents the two junctions connected in parallel. The junction quality is good, $R_{sg}/R_N \approx 12$, but the gap voltage is only $V_g \approx 3.2\,\mathrm{mV}$, which is considerably less than the ~4.0 mV gap ($\Delta_{\mathrm{Nb}} + \Delta_{\mathrm{NbTiN}}$) we expect from this hybrid junction. This probably indicates that the NbTiN counter-electrode in the immediate vicinity of the barrier is of poorer quality.

The spectral response of this mixer was measured with an FTS, and is shown along with the predicted response in Fig. 3. The mixer model, which takes into account the slot-antenna impedance as well as the microstrip tuning circuit, agrees reasonably well with the measured response. The model calculates the surface impedance of the NbTiN films from the measured DC resistivities using the Mattis-Bardeen theory in the local limit,[23] and assumes that there are no excess losses. The effective penetration depths at 800 GHz, taking into account the finite thicknesses of the films, are calculated to be around 330 nm and 310 nm for the ground plane and wiring, respectively. The specific capacitance of the AlN-barrier junctions was assumed to be $85\,\mathrm{fF}\,\mu\mathrm{m}^{-2}$, as was measured using Nb tuning circuits.[19] The frequency width of the measured response indicates that the NbTiN surface resistance has an upper limit of roughly $R_S < 0.1\,\Omega$ near 800 GHz, which is less than the surface resistance of a polycrystalline NbN film.[10] In our mixer, an excess surface resistance of $0.1\,\Omega$ (in the wiring layer only) would translate to an additional ~ 0.5 dB of conversion loss.

Heterodyne noise measurements of the mixer are summarized in Fig 4. For these measurements, the standard Y-factor technique was used, and the equivalent load temperatures were computed using the Callen-Welton formula, $T_{\rm input} = (h\nu/2k)\coth(h\nu/2kT_{\rm load})$. No corrections were applied; the raw Y-factors are plotted with the spectral response curve in Fig. 3. The receiver noise temperature follows the spectral profile measured by the FTS. The best receiver noise temperature was $T_{RX} = 260\,{\rm K}$ at an LO frequency of 798 GHz. The IF output power as a function of bias in response to hot and cold loads at this frequency is shown in Fig. 2. For best noise performance, the mixer should be biased near 2 mV. The first Shapiro step occurs at $V \approx 1.65\,{\rm mV}$, but has been successfully suppressed using a magnetic field. The photon-assisted tunneling step should start at $V = V_{gap} - h\nu/e \approx 0.1\,{\rm mV}$, and the pumped curve gives an indication of this. The LO-pumped *I-V* curve closely matches a theoretical curve calculated from the unpumped *I-V* curve: there is no indication of a gap reduction caused by heating from trapped quasiparticles near the junction, for instance, in the Nb base electrode.

From the heterodyne measurements, we can estimate the mixer conversion loss and compare it to a theoretical value, and thereby obtain an upper limit to the loss in the tuning circuit. Using the shot-noise technique[24] to calibrate the IF system, we estimate that the mixer conversion loss is $L \approx 8.5\,{\rm dB(SSB)}$. Applying Tucker's theory[3] in the 3-port approximation to our mixer, we calculate that the intrinsic mixer conversion loss is 7.0 dB. Together with 0.7 dB loss from the vacuum window, 0.4 dB loss from the beam splitter, and about 0.5 dB loss in the cold optics, the total predicted receiver conversion loss is, $L \approx 8.6\,{\rm dB}$, which closely matches the measured value. This suggests that the loss of the NbTiN tuning circuit has an upper limit comparable to the uncertainty of the measurements ($\sim 1\,{\rm dB}$). This is in agreement with the upper limit on the loss established by modeling the spectral response of the receiver.

To summarize, we have fabricated an NbTiN-based SIS mixer and have demonstrated its low-noise performance up to 850 GHz. In this frequency range, the sensitivity of the mixer is nearly twice as good as previously reported SIS mixers. In our current configuration, about 100 K of the total receiver noise originates from warm beam splitter and cryostat window. We forsee immediate improvement in the receiver performance near 800 GHz by upgrading the optics to a configuration similar to that used in the 850 GHz CSO waveguide receiver.[25] Measurements are now in progress near 1 THz, and it appears promising that NbTiN-based SIS mixers will work up to 1.2 THz.

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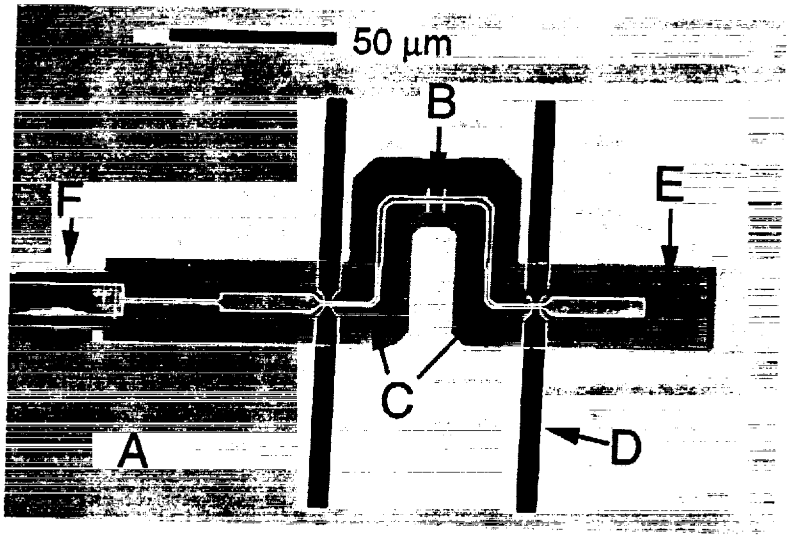

FIG. 1. An SEM image of an 850 GHz mixer. The components of the mixer labeled in the figure are as follows: (A) NbTiN ground plane; (B) two-junction tuning circuit; (C) microstrip transformers; (D) slot antenna; (E) SiO dielectric; (F) IF output transmission line.

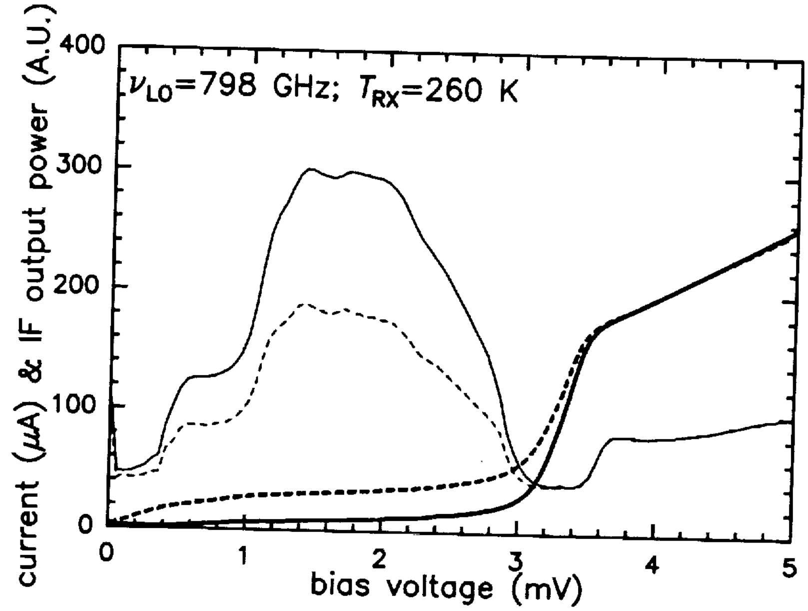

FIG. 2. Current-voltage characteristics of the 850 GHz NbTiN mixer. Shown are the IV curve traced with (dashed heavy) and without (solid heavy) LO power applied at 4.2 K bath temperature. The LO frequency is 798 GHz. The IF power in response to 295 K (solid light) and 77 K (dashed light) loads are shown as a function of voltage bias. The mixer is normally biased near 2.0 mV. For this particular measurement, a 12.5 μm Mylar beam splitter was used to couple the optimum amount of LO power to the mixer, and $T_{RX} = 260\,\mathrm{K}$.

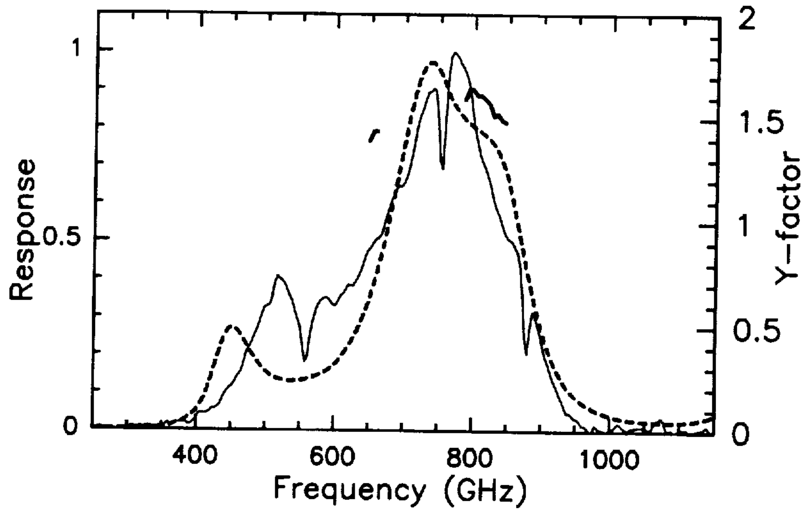

FIG. 3. Direct detection FTS measurement of the mixer's spectral response. The measured response (solid light) is plotted with a model calculation of the response (dashed heavy). These are compared to the Y-factors, the heterodyne response (solid heavy). The dips in the measured spectral response are absorption lines.

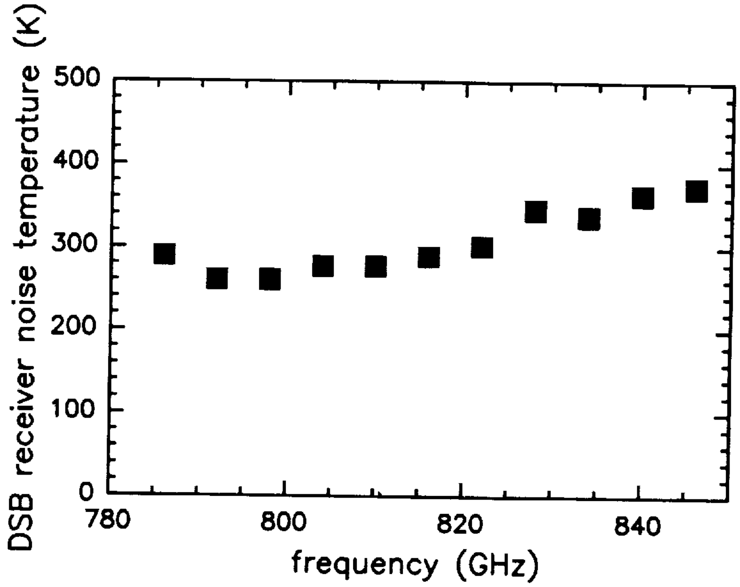

FIG. 4. Receiver noise temperature as a function of frequency across the operating bandwidth of the LO source. This is the same data as presented in Fig. 3. The noise temperature is computed using the Callen-Welton function, which is used to calculate the input power from the thermal loads.