Low-noise 1 THz superconductor–insulator–superconductor mixer incorporating a NbTiN/SiO_2/Al tuning circuit

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Low-noise heterodyne mixing at 1 THz is demonstrated in a quasioptical mixer incorporating Nb superconductor–insulator–superconductor tunnel junctions and a NbTiN/SiO_2/Al tuning circuit. Receiver noise temperatures as low as 250 K at 850 GHz, 315 K at 980 GHz, and 405 K at 1015 GHz are measured—a factor of 2 improvement in sensitivity versus state-of-the-art 1 THz receivers, which incorporate normal metal tuning circuits. An analysis of the receiver sensitivity at 980 GHz demonstrates that NbTiN is low loss up to ~1 THz. [DOI: 10.1063/1.1384005]

Low-noise 1 THz heterodyne mixers are needed to realize the full potential of airborne and space-based telescopes currently being developed for submillimeter astronomy. In recent years, mixers incorporating Nb superconductor–insulator–superconductor (SIS) tunnel junctions and tuning circuits have yielded receiver noise temperatures as low as $(2-3)hf/k_B$ below 680 GHz, the gap frequency of Nb.[1,2] Because rf losses in Nb increase significantly above 700 GHz,[3,4] low-resistivity normal metal (i.e., Al) tuning circuits are preferred to Nb at 1 THz.[5,6] However, tuning circuit losses and shot noise in high-current-density (J_c) Nb/Al–AlO_x/Nb junctions combine to limit the sensitivity of these receivers to ~500 K at 1 THz.[7] The development of high-quality, high-J_c junctions ($J_c > 20\,kA/cm^2$) should yield further sensitivity improvements.[8] However, truly quantum-limited 1 THz receivers will require a superconducting tuning circuit material with a gap frequency >1 THz.

First investigated in the 1960s,[9] and more recently used in rf cavities,[10] NbTiN is a promising candidate to fill this role. Previous work has shown that NbTiN with a transition temperature (T_c) of ~15 K can be integrated with SIS junctions to produce quasioptical[11,12] and waveguide[13] mixers. Using the measured relationship between T_c and the superconducting energy gap in NbN ($F_{gap} \sim 3.52-4.16 k_B T_c/h$),[14,15] it is predicted that these NbTiN tuning circuits are low loss up to 1.05–1.25 THz. However, although a low-noise NbTiN-based SIS receiver has been demonstrated at 800–850 GHz,[16] low-noise THz mixers are yet to be realized.

In this letter, we present a low-noise 1 THz quasioptical mixer in which 1 μm^2 Nb/Al–AlO_x/Nb SIS junctions ($J_c \approx 7.5\,kA/cm^2$) are integrated with a NbTiN/SiO_2/Al tuning circuit. Analyzing the receiver performance, we show that the NbTiN ground plane is low loss up to ~1 THz.

In our quasioptical mixer, a planar twin-slot antenna is integrated with a double-junction tuning circuit, as seen in Fig. 1. The 5-μm-wide microstrip connecting the two junctions (3.8 μm apart) is extended across the antenna slots to rf shorts that pick up the antiphase signals from the antenna. Due to the symmetry of the device, a virtual ground is created between the junctions, producing a parallel inductance to tune out the junction capacitance. Similar designs have previously been shown to efficiently couple radiation to the SIS junctions over broad rf bandwidths.[17,18]

A NbTiN/SiO_2/Al tuning circuit is used for two reasons: (1) to avoid the effects of heat trapping observed previously in Nb SIS junctions integrated with an all-NbTiN tuning circuit[13,19] (replacing one NbTiN layer with Al reduces the effective junction temperature by 1–2 K), and (2) the fear that poor nucleation of NbTiN on SiO_2 may reduce the effective gap frequency of a NbTiN upper wiring layer.[20] (This concern is enhanced by observations that the gap voltage of a typical Nb/Al–AlN_x/NbTiN junction is 3.2–3.5

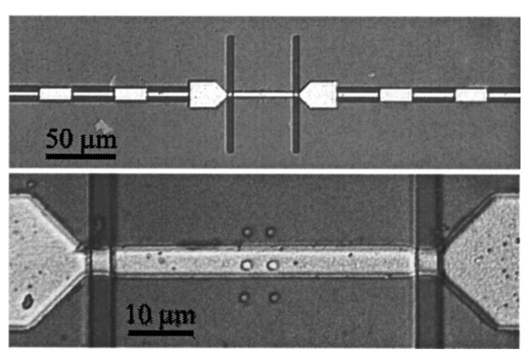

FIG. 1. Optical microscope images of the twin-slot antenna and double-junction tuning structure used here. The SIS junctions are ~1 μm^2.

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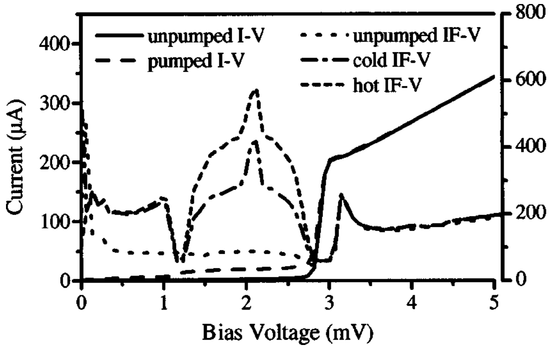

FIG. 2. Bias current and IF output power vs bias voltage for a device measured at 2.9 K with and without 980 GHz local oscillator power. For the pumped measurements, the IF output is measured for 77 and 295 K signal sources, yielding a DSB receiver noise of 315 K at ~2.3 mV.

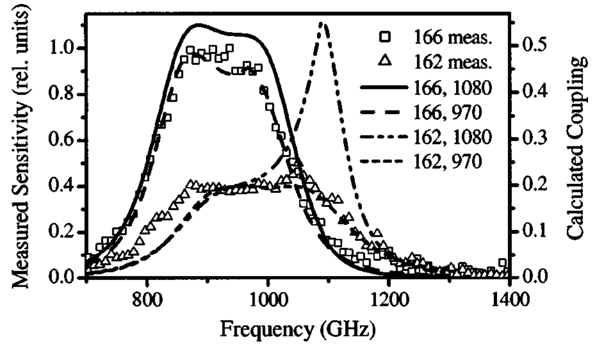

FIG. 3. Direct detection response measured in vacuum at 4.6 K for mixers 166 and 162, with 1.05 and 0.70 μm^2 junctions, respectively. Also shown are the predicted responses of each mixer, assuming NbTiN gap frequencies of 970 and 1080 GHz. The observed drop in device sensitivities at ~1 THz is attributed to increasing loss in the NbTiN.

mV,[8,11,12,16] where 4.0 mV is expected from the energy gap of Nb and the T_c of NbTiN.

Mixers are fabricated on a high-resistivity silicon substrate using a process similar to that described previously for the fabrication of waveguide devices with NbTiN and Al tuning circuits.[13] The 300 nm NbTiN ground plane is deposited at ambient temperature, yielding $T_c = 14.3\,\mathrm{K}$ and a normal-state conductivity of $\sigma_{20\,\mathrm{K}} \approx 0.9\times 10^6\,\Omega^{-1}\,\mathrm{m}^{-1}$.[21] The SiO_2 dielectric layer is ~250 nm thick, while the 400 nm Al wiring layer has $\sigma_{4\,\mathrm{K}} \sim 2\times 10^8\,\Omega^{-1}\,\mathrm{m}^{-1}$, and is expected to be in the anomalous limit.[22] The Al wiring layer is protected against chemical attack by 200 nm of SiO_2, and contact optical lithography is used for all structure definition steps.

As seen in Fig. 2, measurements of a mixer at 2.9 K yield good current–voltage characteristics, with $V_{\mathrm{gap}} = 2.89\,\mathrm{mV}$ and $R_n = 13.3\,\Omega$. No hysteresis is observed at the gap voltage, indicating that heating of the junctions is minimal in these devices, as expected. $R_nA \approx 28\,\Omega\,\mu\mathrm{m}^2$ is estimated from measurements of large area junctions, yielding $A \approx 1.05\,\mu\mathrm{m}^2$ per junction for this device.

For receiver measurements, mixers are fixed with wax to an antireflection-coated 10 mm elliptical silicon lens that is clamped to a mixer block on the 4 K stage of an optical cryostat. Radiation is coupled into the mixer through a 12 μm Kapton™ vacuum window at 295 K and Zitex™ G104 heat filters at 77 and 4 K. The direct detection response of the device is measured in vacuum with a Fourier transform spectrometer, while heterodyne sensitivity is measured using 295 and 77 K blackbody sources, backward-wave local oscillators operating between 850 and 1100 GHz, and 6 and 14 μm Mylar™ beamsplitters. The intermediate frequency (IF) output from the mixer is amplified, bandpass filtered, and measured with a power meter. The receiver noise temperature and gain are determined using the Callen–Welton formulation for the blackbody signal powers.[23] Using the unpumped mixer as a noise source, the noise and gain of the IF system are found to be 4.3 K and 68 dB in an 85 MHz band centered at 1.46 GHz.

The direct detection response of the receiver is shown in Fig. 3 for two mixers: One with 1.05 μm^2 junctions (166), and one with 0.7 μm^2 junctions (162) (they are otherwise identical). Also shown are calculations of the coupling of radiation from the antenna to the junctions for each mixer (the NbTiN surface impedance is calculated in the local limit, using the frequency-dependent conductivity of a superconductor in the anomalous limit[3]). Qualitative fits to the response of mixer 166 for NbTiN gap frequencies ($F_{\mathrm{gap,NbTiN}}$) of 970 and 1080 GHz are obtained by using the junction separation and specific capacitance, the transformer length, and the NbTiN normal-state resistivity as fit parameters. Using these fitted values, the corresponding response of mixer 162 is calculated. From Fig. 3, it is seen that using $F_{\mathrm{gap,NbTiN}} = 1080\,\mathrm{GHz}$, the response of device 162 is greatly overestimated at frequencies above 1 THz. Significantly better agreement is obtained with $F_{\mathrm{gap,NbTiN}} = 970\,\mathrm{GHz}$.

The double-sideband (DSB) receiver noise temperatures of mixer 166 at 2.9 K and mixer 162 at 4.6 K are shown in Fig. 4. Using device 166, an optimum uncorrected receiver noise temperature of 250 K is measured at 850 GHz (*Y*-factor = 2.20 dB). The noise temperature remains low up to ~1 THz (315 K at 980 GHz), but rises significantly at higher frequencies (405 K at 1015 GHz). Note that Fig. 2 includes plots of the current and IF output versus bias voltage for device 166 pumped at 980 GHz.

Focusing on the results obtained with device 166 at 980 GHz, the receiver sensitivity is analyzed to estimate the loss in the NbTiN/SiO_2/Al tuning circuit. In this analysis, the two 1.05 μm^2 junctions are replaced by one 2.1 μm^2 junction ($R_n = 13.3\,\Omega$), and the mixer gain is calculated using the three-port Tucker theory[24] and an embedding admittance

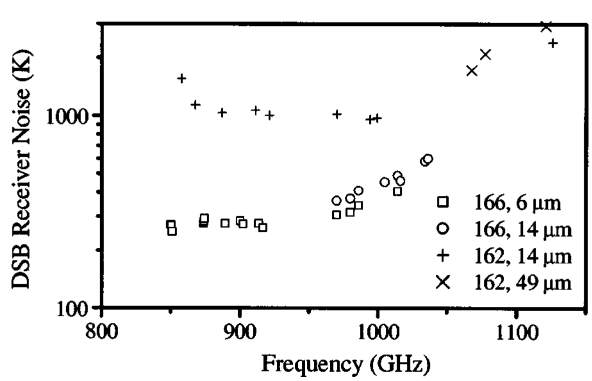

FIG. 4. DSB receiver noise temperatures of mixers 162 and 166 as a function of frequency. Mixer 166 is measured at 2.9 K using 6 and 14 μm beamsplitters, while mixer 162 is measured at 4.6 K with 14 and 49 μm beamsplitters and a thick vacuum window (100 μm Mylar™).

($Y_{emb}=0.36+0.09i\,\Omega^{-1}$) that is estimated from the current–voltage characteristics in Fig. 2 using the rf voltage match method.[25] When the calculated DSB mixer gain (−7.2 dB) and optical loss (1.2 dB) are subtracted from the measured receiver gain (−11.1 dB), a 2.7 dB loss remains—this is attributed to the tuning circuit.

Assuming NbTiN to be an ideal superconductor with $F_{gap}=970$ GHz, a calculation of the direct detection response of device 166 (see Fig. 3) predicts a loss in the Al wiring of ~2.3 dB. (The surface impedance of the NbTiN is calculated in the local limit, using the frequency-dependent conductivity of a superconductor in the anomalous limit,[3] while the Al is assumed to be in the anomalous limit.[22]) Subtracting this 2.3 dB from the 2.7 dB tuning circuit loss, the loss in the NbTiN is estimated to be 0.4 dB. The accuracy of this estimate (1 dB) is limited by uncertainties in the optical losses, the embedding admittance, and the Al surface resistance. However, it is also assumed that the antireflection coating on the Si lens is ideal, and that the Al portions of the rf choke, the SiO_2 dielectric, and the Nb junction electrodes are all lossless. Thus, it is concluded that the NbTiN ground plane is relatively low loss at 980 GHz. Note that a similar analysis at 850 GHz estimates the loss in the NbTiN to be 0.5 dB (versus 3 dB in the Al).

The observed drop in receiver sensitivity above 1 THz is also observed in waveguide mixers with a NbTiN/SiO_2/Al tuning circuit,[20] providing additional evidence that it is not attributable to the device design, but rather to increasing loss in the NbTiN. The estimated NbTiN gap frequency of 970 GHz is significantly lower than the 1.05–1.2 THz that is expected for $T_c=14.3$ K. This reduction is not fully understood, but it is thought to be related to vertical and lateral nonhomogeneities observed in the electrical properties of NbTiN films grown at room temperature[26]—resistive measurements of T_c probe the path of least resistance in the film, while THz radiation in a microstrip probes the entire layer (the magnetic penetration depth in the 300 nm NbTiN film is estimated to be 290 nm).

Despite this uncertainty, one potential means of increasing the gap frequency is clear—the use of NbTiN with a higher T_c. Additional improvements in receiver sensitivity may be obtained by incorporating high-quality, high-current-density Nb/Al–AlN_x/Nb junctions to reduce the loss in the NbTiN/SiO_2/Al tuning circuit.[8]

In conclusion, we have presented a low-noise 1 THz SIS mixer incorporating Nb SIS junctions and a NbTiN/SiO_2/Al tuning circuit. Receiver noise temperatures as low as 250, 315, and 405 K have been measured at 850, 980, and 1015 GHz, respectively—a factor of 2 improvement over the best previously reported 1 THz receiver sensitivity (840 K at 1042 GHz for a device with an Al tuning circuit[6]). This improvement is enabled by the low-loss performance of the NbTiN ground plane up to ~1 THz.

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