$NbTiN/SiO_2/NbTiN$ and $NbTiN/SiO_2/Al$ tuning circuits for 1 THz waveguide SIS mixers

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ABSTRACT

Waveguide SIS mixers are presented in which $Nb/Al\text{-}AlO_x/Nb$ tunnel junctions are integrated with both $NbTiN/SiO_2/NbTiN$ and $NbTiN/SiO_2/Al$ tuning circuits. The mixers with a $NbTiN/SiO_2/NbTiN$ tuning circuit yield relatively low receiver noise temperatures between 700 and 830 GHz, but their sensitivity drops significantly above ~ 850 GHz. In contrast, low-noise heterodyne mixing near 1 THz is observed in mixers incorporating a $NbTiN/SiO_2/Al$ tuning circuit. In particular, an uncorrected receiver noise temperature of 585 K is measured at 970 GHz. From an analysis of the receiver sensitivity and gain, it is determined that the loss in the NbTiN ground plane is low (≤ 0.6 dB) below 970 GHz. A decrease in receiver sensitivity above 1 THz is attributed to an onset of rf loss in the NbTiN.

1. INTRODUCTION

The specifications of the HIFI instrument for the Far-Infrared Space Telescope (FIRST) require the development of THz SIS mixers with receiver noise temperatures of 3.5hν/k (i.e. 160 K at 960 GHz). Although mixers incorporating $Nb/Al\text{-}AlO_x/Nb$ tunnel junctions and Nb wiring layers have been shown to yield receiver noise temperatures as low as 2hν/k below the 680 GHz superconducting gap frequency of Nb [1], Nb tuning circuits become very lossy at higher frequencies [2]. Indeed, above 800 GHz, wiring of a high-conductivity normal metal, such as aluminum, has been shown to yield significant improvements in receiver sensitivity [3], with a best-reported receiver sensitivity of 840 K at 1042 GHz [4]. However, it has also been shown that losses in the Al wiring layers and excess shot-noise in high-J_c $Nb/Al\text{-}AlO_x/Nb$ SIS junctions ($J_c > 10$ kA/cm^2) combine to limit the sensitivity of these receivers to ~ 500 K at 1 THz [5-6].

A significant improvement in 1 THz receiver sensitivity will require a corresponding reduction in tuning circuit losses. This may be achieved in two ways. Certainly, an improvement in the quality of high-J_c SIS junctions will yield a reduction in the noise of mixers with normal-metal tuning circuits. However, the ultimate goal of producing quantum-limited THz receivers will require the development of low-loss superconducting wiring layers with a gap frequency of ~ 1.2 THz or higher. NbTiN, a compound superconductor previously used for thin-film coatings in rf cavities [7], is one promising candidate to fill this need.

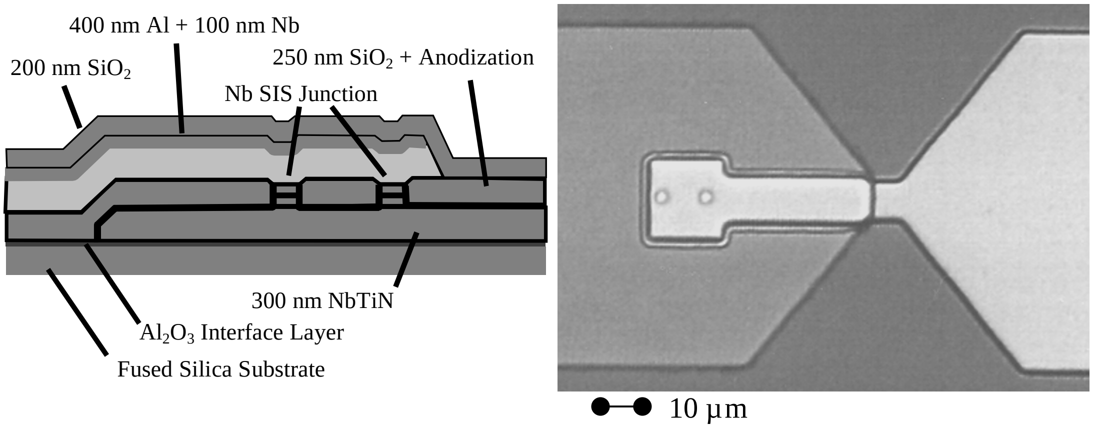
Previous work has shown that NbTiN layers with T_c = 14.3-15.5 K can be integrated with Nb-based SIS tunnel junctions to produce both quasi-optical [8-9] and waveguide [10-11] mixers. Based on the BCS relationship between T_c and the superconducting energy gap ($F_{gap} \sim 3.52 \cdot k_B T_c / h$), it is expected that these NbTiN-based tuning circuits will be low-loss up to 1.05-1.14 THz. Indeed, the observation of AC Josephson resonances in I-V characteristics at voltages up to 2.2 mV provides evidence of low-loss performance around 1 THz in these tuning circuits [8-9,11]. Furthermore, the recent demonstration of a receiver noise temperature of 205 K at 798 GHz for a mixer incorporating a NbTiN tuning circuit [12] confirms that NbTiN wiring layers are very low-loss up to at least 800 GHz. However, despite these promising results, it remains to be shown that that NbTiN tuning circuits can be used to produce low-noise receivers for frequencies up to ~ 1.2 THz.

In this paper, we demonstrate waveguide SIS mixers in which standard Nb/Al-AlO_x/Nb tunnel junctions are integrated with NbTiN/SiO_2/NbTiN and NbTiN/SiO_2/Al tuning circuits. The direct-detection and heterodyne sensitivities of these devices are presented for frequencies between 0.7 and 1.05 THz. Additionally, the receiver noise and conversion gain of a mixer with a NbTiN/SiO_2/Al tuning circuit are analyzed to evaluate the RF performance of the NbTiN ground plane at 970 GHz. The parallel development of a quasi-optical THz mixer with a NbTiN/SiO_2/Al tuning circuit is discussed elsewhere in these proceedings [13].

All of the receiver noise temperatures presented here are calculated using Planck-corrected effective temperatures for the blackbody signal loads and the receiver optics. Corrected noise temperatures, calculated from the measured receiver noise using estimates of the frequency-dependent loss in the receiver optics (beamsplitter, vacuum window, heat-filter, and lens) are also presented. This allows the intrinsic mixer performance to be more easily evaluated. Furthermore, the corrected noise temperatures can be directly compared with the HIFI mixer specifications, which are defined for the ideal case of zero optical loss in front of the mixer.

2. MIXER DESIGN AND FABRICATION

THz mixers are fabricated by integrating standard 1-µm Nb SIS junctions ($J_c \sim 7.5$ kA/cm^2) with a 300-nm NbTiN ground plane and either a 400-nm NbTiN or a 400-nm Al + 100-nm Nb wiring layer, as seen in Fig. 1a. The twin-junction tuning circuit shown in Fig. 1b is used to efficiently couple radiation from the waveguide probes to the SIS junctions over a relatively broad rf bandwidth. A 10-µm wide microstrip transmission line connects the two junctions, which are separated by 4-7 µm. The



(a) (b)

Figure 1. a) Cross-section of the NbTiN/SiO_2/Al tuning circuit (in the NbTiN/SiO_2/NbTiN tuning circuit, the Al + Nb wiring is replaced with 400-nm of NbTiN and the 200 nm SiO_2 passivation layer is not present). b) Optical microscope image of the twin-junction tuning circuit. The optically defined SIS junctions are nominally 1 μm^2. The transformer length and junction separation are varied to tune the circuit resonance.

junctions are connected to the waveguide probes by a microstrip impedance transformer 6-µm wide and 18-26 µm long. The waveguide probes and the rf choke structures (not shown) are designed for a 1 THz waveguide mixer block with waveguide and substrate channel dimensions of 120×240 μm^2 and 90×90 μm^2, respectively. Table 1 summarizes the tuning circuit geometries of the six devices for which results are presented in this paper.

The mixers are fabricated on 200-µm thick fused quartz substrates using processes similar to those described previously for the fabrication of devices with NbTiN and Al striplines [10,11,14]. The primary differences with respect to the previously described

Table 1. Tuning circuit parameters for the six devices discussed here.

	NbTiN / SiO_2 / NbTiN		NbTiN / SiO_2 / Al			
Device #	c14	c72	c07	c13	c37	c71
Tuning Section	7x10	4x10	5.5x11	7x11	5.5x11	4x11
Transformer	26x6	20x6	20x7	23x7	20x7	18x7
Junction Area	1.0	1.0	0.58	0.58	0.67	0.64
Wiring Layer	400 nm NbTiN, 14.3 K		400 nm Al + 100 nm Nb			
Dielectric	~ 250 nm SiO_2		~ 250 nm SiO_2			
Junction	Nb/Al-AlO_x/Nb, 28 $\Omega\cdot\mu m^2$		Nb/Al-AlO_x/Nb, 28 $\Omega\cdot\mu m^2$			
Ground Plane	300 nm NbTiN, 14.3 K		300 nm NbTiN, 14.3 K			

(all lengths and widths are given in µm, junction areas are in μm^2)

processes are: (1) the Al + Nb wiring layer is defined using a lift-off process (instead of the etch process used for a NbTiN wiring layer), and (2) in the devices with the Al + Nb wiring, a 200-nm SiO_2 passivation layer is added to protect the Al from chemical attack. The NbTiN ground plane and wiring layer are deposited using a process that was previously shown [10,15] to reproducibly produce films with T_c = 14.3-14.4 K and $\sigma_{16K} \approx 0.9\times10^6\ \Omega^{-1}m^{-1}$. Based on previous measurements, the sputtered Al layer is expected to be in the anomalous limit, with $\sigma_{4K} \approx 2\times10^8\ \Omega^{-1}m^{-1}$. Note that Nb is added to the top of the Al wiring layer to reduce the dc and IF series resistance of the upper wiring layer portion of the rf choke structure.

3. DC I-V CHARACTERISTICS

Representative dc current-voltage characteristics are shown in Fig. 2 for one mixer with a NbTiN/SiO_2/NbTiN tuning circuit (c14) and one mixer with a NbTiN/SiO_2/Al tuning circuit (c37). For the devices with a NbTiN/SiO_2/NbTiN tuning circuit, measurements at 4.6 K yield V_{gap} = 2.6-2.63 mV, $R_n\cdot A \approx 28\ \Omega\cdot\mu m^2$, $R_n \approx 14\ \Omega$ (thus, $A \approx 1.0\ \mu m^2$ per junction), and $R_{2.0}/R_n$ = 14-17. In comparison, measurements at 4.6 K of the devices with a NbTiN/SiO_2/Al tuning circuit yield V_{gap} = 2.7-2.82 mV, $R_n\cdot A \approx 28\ \Omega\cdot\mu m^2$, R_n = 20-24 Ω (thus, A = 0.58-0.7 μm^2 per junction), and $R_{2.0}/R_n$ = 10-17. Measurements of these same devices at ~ 2.8 K yield an improvement in junction quality – V_{gap} = 2.84-2.90 K and $R_{2.0}/R_n$ = 13-40.

One point of note is that dc heating of the junction electrodes is minimal in the devices with a NbTiN/SiO_2/Al tuning circuit, as seen from the large gap voltage and the absence of back-bending in the current-voltage characteristic of device c37 in Fig. 3. This is in contrast to both present and previously reported [11] results from devices with a NbTiN/SiO_2/NbTiN tuning circuit. This previously observed dc heating has since been shown to be caused by the presence of a heat-flow barrier at the Nb/NbTiN interfaces due

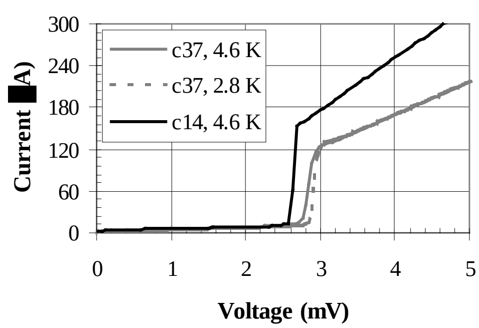


Figure 2. Current-voltage characteristics of a device with a NbTiN/SiO_2/NbTiN tuning circuit (c14) measured at 4.6 K and a device with a NbTiN/SiO_2/Al tuning circuit (c37) measured at 4.6 K and 2.8 K. The gap suppression in c14 is attributed to heat trapping in the junction electrodes due to the large superconducting energy gap in NbTiN relative to that in Nb [16].

to the larger superconducting energy gap of NbTiN relative to that of Nb [16]. Replacing one NbTiN layer with Al removes this barrier, allowing heat to escape from the junction into the Al wiring.

4. RF MEASUREMENT SETUP

RF measurements are performed in both tuneable and fixed-tuned 1-THz waveguide mixer blocks. The tuneable mixer block, previously used in the study of Al-stripline SIS mixers [3], is a split-block design incorporating a sliding backshort tuner, while the fixed-tuned mixer block has a stamped backshort cavity extending 60 µm from the bottom of the substrate channel. Both mixer blocks have a 120x240 μm^2 waveguide, a 90x90 μm^2 substrate channel, and a diagonal horn with an 11° cone angle. Radiation is coupled into the mixer block through a 100-µm Mylar vacuum window at 295 K, a Zitex G104 heat-filter at 77 K, and a high-density polyethylene lens at 4 K.

The direct-detection spectral response of the mixer is measured using a Michelson interferometer in which the optical path can be evacuated to eliminate water vapour absorption lines. Heterodyne sensitivity is measured using a 295-K / 77-K hot-cold measurement, a carcinotron plus doubler operating between 700 and 740 GHz, BWOs operating between 830 and 1100 GHz, and Mylar beamsplitters of 6, 14, and 49 µm thickness. IF output power from the device is coupled to the cryo-amplifier through a bias-T and an isolator. Following amplification at 4 K, the signal is further amplified and bandpass filtered at room temperature. Using an unpumped mixer as a calibrated noise source, the noise and gain of the IF system are determined to be 3-5 K and ~ 68 dB at 1.46 GHz, over an 85 MHz band-width.

Fig. 3 presents the estimated rf transmission spectra of each of the optical elements in the signal path. The transmissions of the 14 and 49 µm beamsplitters have been calibrated using the Michelson interferometer and a SIS mixer as a direct detector in the 800-1000 GHz range, while the transmission of the 6 µm beamsplitter and 100 µm vacuum window are calculated from previously measured optical properties of Mylar. The transmission of the lens is approximated as a sum of an absorption loss in 3 mm of

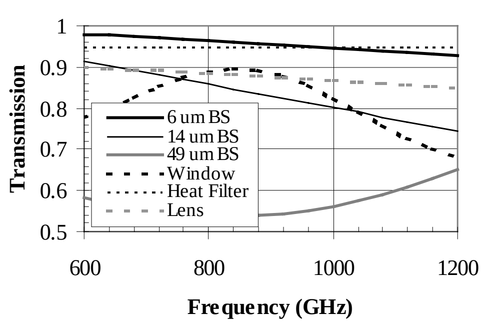


Figure 3. Estimated transmissions of the optical components in the signal path.

HDP (an approximate average thickness for the lens) plus incoherent reflection losses at each surface. The rf loss in the Zitex heat-filter is low enough to be hard to accurately measure. As a rough estimate, a loss of 5% is assumed.

5. NbTiN/SiO_2/NbTiN TUNING CIRCUIT DEVICE RESPONSE

The direct-detection and heterodyne response of the two devices with a NbTiN/SiO_2/NbTiN tuning circuit are shown in Fig. 4. Both devices are measured using the tuneable mixer. Each direct-detection response curve is for a fixed backshort position – curves c14 and c72a are for a 60 µm backshort depth, while curve c72b is for a backshort depth of 180 µm. For the heterodyne measurements, the backshort position is optimized at each frequency. The mixer block temperature is ~ 4.6 K for all of these measurements.

Considering the direct-detection results in Fig. 4a, it is noted that the spectral response of these devices agrees with qualitative predictions of the tuning circuit performance – for the two devices presented here, decreasing the separation from 7 µm (c14) to 4 µm (c72) shifts the resonance to a higher frequency. Unfortunately, a quantified comparison of the measured and predicted device responses is difficult due to a lack of 3-D electromagnetic simulations and/or scale-model measurements of the waveguide, waveguide probe, and rf choke designs used in this work. Thus, it is difficult to use the measured direct-detection response to verify the rf properties of the NbTiN ground plane and wiring layers.

From the heterodyne results in Fig. 4b, it is seen that these devices are relatively

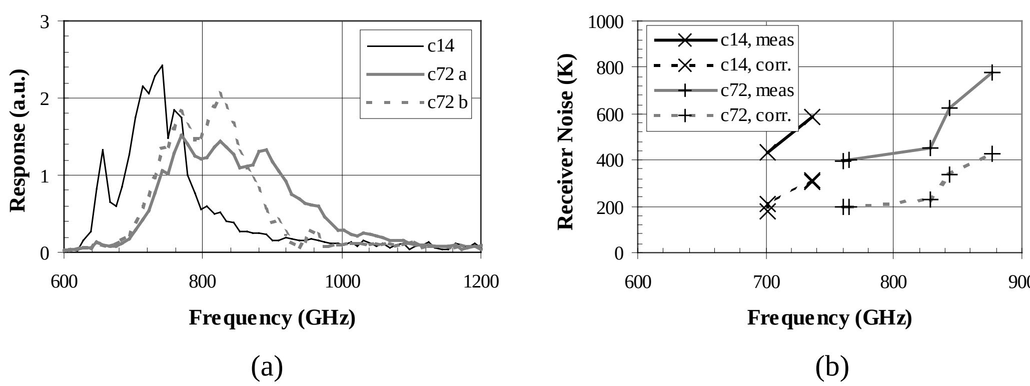


Figure 4. (a) Fixed-tuned direct-detection response of the two devices with a NbTiN/SiO_2/NbTiN tuning circuit. Both devices are measured in the tuneable mixer (c14 and c72a – depth = 60 µm, c72b – depth = 180 µm). (b) Measured and corrected receiver noise temperatures for the same two devices. The corrected noise temperatures are calculated from the uncorrected data and the estimated optical losses in the beamsplitter, dewar window, heat-filter, and lens (see Fig. 3 for the loss estimates).

sensitive in the 700-830 GHz range – device c14 produces a receiver noise temperature of 435 K at 700 GHz, while c72 produces noise temperatures of 395 and 455 K at 760 and 830 GHz, respectively. Correcting for the previously estimated losses (see Fig. 3) in the 14 µm beamsplitter, vacuum window, heat-filter, and lens, the effective noise at the mouth of the horn is estimated to be ~ 190-235 K over the same frequency range.

The relatively low-noise performance of these devices demonstrates that the NbTiN/SiO_2/NbTiN tuning circuits are relatively low-loss up to at least 830 GHz. However, one point of concern is the general absence of high sensitivity above 850 GHz in these, and other, devices with a NbTiN/SiO_2/NbTiN tuning circuit. This may be partially attributed to spreading inductances introduced by the embedding of the 1-µm junctions in a 10-µm wide microstrip (these will effectively lengthen the tuning section, pushing the circuit resonances to lower frequencies). However, the concern is that, due to poor nucleation of NbTiN on SiO_2, a poor-quality interface layer may be present at the bottom of the NbTiN wiring layer. This interface layer, which could be of non-negligible thickness, may introduce excess tuning circuit loss at frequencies well below the predicted NbTiN gap frequency.

Independent of the rf properties of the NbTiN ground plane and wiring layer, the direct-detection response of device c72 does demonstrate that a moderate improvement in rf coupling can, for some devices, be obtained by tuning the backshort cavity depth. Thus, it is hoped that further improvements in receiver sensitivity may be obtained by a careful optimization of the integrated design of the waveguide, rf choke structure, waveguide probes, and on-chip tuning structure. However, increasing the cavity depth to improve the peak sensitivity also introduces a high-frequency cut-off, reducing the fixed-tuned bandwidth of the device. Thus, the potential for improved sensitivity may be limited by rf bandwidth specifications (i.e. 800-960 GHz and 960-1120 GHz for HIFI Bands 3 and 4).

As a final note on the results presented in Fig. 4, the 70 GHz ripple seen in the direct-detection response of device c72 is observed in the direct-detection responses of a range of waveguide and quasi-optical devices, in multiple measurement cryostats. Thus, it is believed to be an intrinsic property of the measurement instrument.

6. NbTiN/SiO_2/Al TUNING CIRCUIT DEVICE RESPONSE

The fixed-tuned direct-detection responses of the four devices with a NbTiN/SiO_2/Al tuning circuit are shown in Fig. 5. Devices c07, c13, and c71 are measured in the tuneable mixer block – the response of c13 and c71 are shown for a backshort depth of 60 µm, while the two curves shown for c07 correspond to backshort depths of 60 µm and 120 µm. Device c37 is measured in a fixed-tuned mixer block with a 60-µm deep stamped backshort cavity. Note that the Michelson interferometer is evacuated to eliminate water vapour absorption lines in all of these measurements.

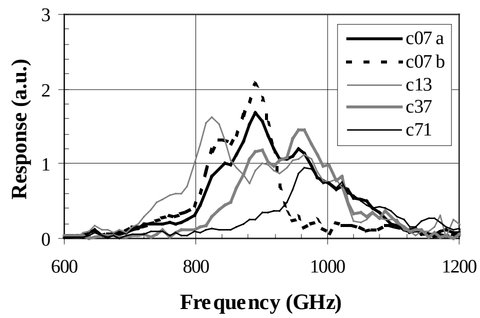
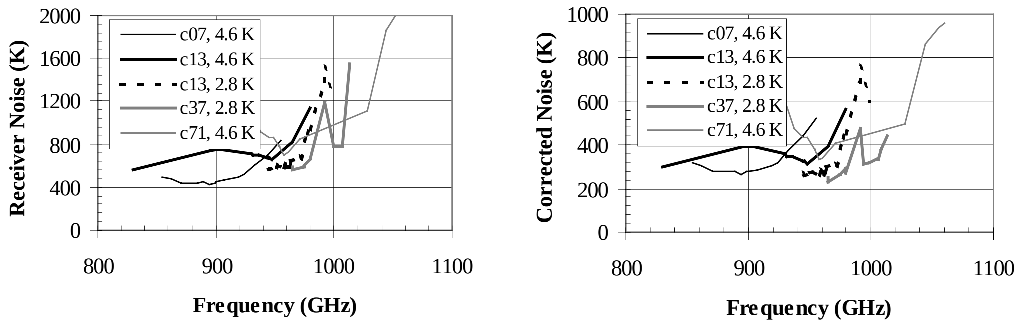


Figure 5. Fixed-tuned direct-detection response of the four devices with a NbTiN/SiO_2/Al tuning circuit. Devices c07, c13 and c71 are measured in the tuneable mixer (c07a, c13, c71 – depth = 60 µm, c07b – depth = 120 µm). Device c37 is measured in a fixed-tuned mixer (depth = 60 µm). All measurements are performed in vacuum.

As was the case for the devices with a NbTiN/SiO_2/NbTiN tuning circuit, the direct-detection response of these mixers agrees qualitatively with predictions of the tuning circuit performance – decreasing the junction separation from 7 µm (c13) to 5.5 µm (c07 and c37) and 4 µm (c71) causes the resonance to shift to higher frequency, as is expected. Unfortunately, the lack of a detailed model for the embedding impedance of the mixer make it difficult to use these results to quantify the rf properties of the NbTiN ground plane. However, it is noted that all four devices share a similar high-frequency roll-off at ~ 1 THz, despite having significantly different low-frequency roll-offs. This high frequency cut-off is believed to be evidence of increasing rf loss in the NbTiN ground plane above 1 THz.

The measured receiver noise temperatures for the same four devices are shown in Fig. 6a for measurements at 4.6 K and ~ 2.8 K. Uncorrected receiver noise temperatures as low as 445 K at 895 GHz (at 4.6 K, with a 6 µm beamsplitter) and 585 K at 970 GHz (at ~ 2.8 K, with a 14 µm beamsplitter) are obtained. Furthermore, 3 combinations of junction separation, transformer length, and junction area (c13, c37, and c71) produce similar responses near 1 THz, with receiver noise temperatures and conversion losses of 585-620 K and 12-13 dB at 950-970 GHz. Note that the ~ 20 % improvement in the response of device c13 upon cooling from 4.6 to 2.8 K is typical of the improvement observed in these devices.

Combining the estimated optical losses in front of the mixer (see Fig. 3) with the Planck-corrected temperatures of each element, the measured receiver noise temperatures in Fig. 6a are corrected and replotted in Fig. 6b. The resulting corrected noise temperatures at 4.6 K are 275 K at 895 GHz for device c07 and 320-350 K at 950-970 GHz for devices c13, c37, and c71. The corrected receiver sensitivities at 2.8 K for devices c13, c37, and c71 are 260-285 K at 950-970 GHz.



(a) (b)

Figure 6. (a) Measured receiver noise temperatures for the four devices with a NbTiN/SiO_2/Al tuning circuit. c07 and c71 are tuned measurements, while c13 and c37 are fixed-tuned measurements. The observed improvement in sensitivity upon cooling for c13 is representative of the effect also seen in c37 and c71 (~ 20 % from 4.6 to 2.8 K). (b) Corrected noise temperatures calculated from the uncorrected data in (a) and the optical loss estimates in Fig. 3 for the beamsplitter, vacuum window, heat-filter, and lens.

The dip in receiver sensitivity at 980-990 GHz seen in Fig. 6 for both c13 and c37 is due to an atmospheric water vapour absorption line. Independent of this absorption line, the noise temperatures of devices c13, c37, and c71 all rise significantly above 1 THz. This agrees with the previously noted drop in direct-detection sensitivity in this frequency range, giving further evidence of an onset of rf loss in the NbTiN ground plane above 1 THz.

7. NbTiN GROUND PLANE LOSS ANALYSIS

Focussing on the device that produces the highest receiver sensitivity near 1 THz (c37 at 2.8 K), the receiver noise and gain at 970 GHz are analyzed to identify the factors limiting sensitivity. To simplify the analysis, the twin-junction tuning circuit is approximated by a single SIS junction with an area equal to the total area of the two junctions ($A = 1.34\ \mu m^2$, $R_n = 21\ \Omega$). Using the rf voltage match method [17] and measured pumped and unpumped I-V characteristics, the embedding admittance for the model junction is estimated to be $0.12 + 0.037i\ \Omega^{-1}$ at 970 GHz. Using this embedding

Table 2 – Receiver noise and gain breakdown for c37 at 970 GHz and 2.8 K

	T_N (K)	G (dB)
Optics	126	-2.4
Tuning Circuit	0	-3.2
Mixer (DSB)	$77 + h\nu/2k_B$	-7.2
IF chain	5	0
Total Receiver	586	-12.9

admittance, the DSB mixer gain and noise are calculated using the 3-port Tucker theory [18]. Note that the mixer noise calculation also includes a bias-dependent charge quantization ($q/e = 1 + 0.45 \cdot V_{gap}/V_{bias}$) to account for the enhancement of shot-noise by multiple Andreev reflection [19].

From this analysis (summarized in Table 2), it is determined that there is ~ 3.2 dB of excess loss at the input to the mixer, after correcting for the estimated losses in the receiver optics. As a first-order approximation, this loss is attributed to the NbTiN/SiO_2/Al tuning circuit. A separate calculation of the coupling of radiation from the waveguide probes to the SIS junctions predicts a loss in the Al wiring layer of 2.6 dB (assuming the Al to be in the anomalous limit, with $\sigma_{4K} = 2\times10^8\ \Omega^{-1}m^{-1}$, and NbTiN to be a loss-less superconductor). The remaining 0.6 dB is thus an estimate of the loss in the NbTiN ground plane.

Unfortunately, the accuracy of this estimate is limited by uncertainties in the optical losses, the embedding admittance, and the surface resistance of the Al wiring layer. However, it is also assumed that the waveguide, the Al/Nb portion of the rf choke, the SiO_2 dielectric layer, and the Nb junction electrodes each contribute zero rf loss. Thus, it seems safe to say that the NbTiN ground plane used in these devices is, indeed, relatively low-loss at frequencies up to 970 GHz.

8. DISCUSSION

Reviewing the receiver noise analysis summarized in Table 2, it is noted that there is room for further improvement. In particular, the estimated tuning circuit loss and DSB mixer noise are both relatively high (3.2 dB and 77 K, respectively). Thus, it may be possible to produce a somewhat more sensitive device if a similar tuning circuit loss can be combined with junctions with lower leakage currents. Furthermore, it is expected that the incorporation of recent improvements in the fabrication of very-high current-density junctions (J_c ~ 30 kA/cm^2) [20-21] should make it possible to significantly reduce the tuning circuit loss while maintaining, or even reducing, the mixer shot-noise.

Although the mixers with a NbTiN/SiO_2/Al tuning circuit yield promising results at frequencies up to 970 GHz, the observed sensitivity cut-off at ~ 1 THz remains a concern. In particular, this is ~ 50 GHz lower than the gap frequency estimated from the BCS relationship between T_c and the superconducting energy gap ($F_{gap} \sim 3.52 \cdot k_B T_c/h$ and T_c = 14.3 K predict F_{gap} ~ 1050 GHz). There are several possible explanations for this discrepancy between the predicted and measured cut-off frequencies. Of these, two are:

1. The T_c of the NbTiN film used here is lower than has been demonstrated for films deposited on an MgO substrate or at an elevated substrate temperature (T_c ~ 16-17 K) [8]. Thus, it is possible that the physical mechanisms that reduce T_c in these films may also affect the relationship between the energy gap and T_c.

2. Because the estimated penetration depth in the NbTiN ground plane is approximately equal to the layer thickness (290 nm vs. 300 nm), radiation in the tuning circuit will penetrate to the bottom of the NbTiN layer. Thus, if the initial stages of NbTiN film growth produce a poor-quality interface layer, that layer could induce loss in the tuning circuit below the predicted NbTiN gap frequency.

Additional measurements and analysis are needed to fully explain the upper cut-off frequency of these tuning circuits. However, one means of improvement is clear – the use of higher-T_c NbTiN layers deposited on MgO and/or elevated-temperature substrates. This should increase the cut-off frequency at least proportionally to the increase in T_c (i.e. to at least 1120 GHz for T_c = 16 K). Note that the high dielectric constant of MgO makes it less desirable than fused quartz as a substrate material for waveguide mixers. However, an MgO substrate would be compatible with a quasi-optical mixer design, such as that presented elsewhere in these proceedings [13].

9. CONCLUSIONS

SIS mixers in which standard Nb SIS junctions are integrated with NbTiN/SiO_2/NbTiN and NbTiN/SiO_2/Al tuning circuits have been fabricated and tested as both direct and heterodyne detectors.

Mixers with a NbTiN/SiO_2/NbTiN tuning circuit produce receiver noise temperatures as low as 395-455 K between 700 and 830 GHz. Correcting for optical losses, the corresponding effective noise at the mouth of the horn is estimated to be 195-235 K. From this relatively low-noise performance, it is clear that the NbTiN/SiO_2/NbTiN tuning circuits are relatively low-loss up to at least 830 GHz. However, the poor sensitivities of these devices above 850 GHz raise concerns that a poor-quality interface layer at the bottom of the NbTiN wiring layer may introduce tuning circuit losses below the NbTiN gap frequency.

Using mixers with a NbTiN/SiO_2/Al tuning circuit, receiver noise temperatures as low as 445 and 585 K are obtained at 900 and 970 GHz, respectively. Correcting for the optical losses in front of the horn of the mixer yields corrected noise temperatures as low as 260 K at 970 GHz. These results represent the first demonstration of relatively low-noise performance in a 1 THz SIS mixer incorporating a NbTiN-based tuning circuit. Furthermore, this represents a significant improvement over the best previously reported 1 THz receiver sensitivity (840 K at 1042 GHz for an Al stripline device [4]).

Analyzing the device with the highest sensitivity at 970 GHz, it is determined that the most significant contributions to the corrected receiver noise are a DSB mixer noise of 77 K and 3.2 dB of rf loss in front of the mixing element. Of this 3.2 dB, the Al wiring layer is estimated to contribute 2.6 dB of loss. The remaining 0.6 dB is thus an estimate of the loss in the NbTiN ground plane at 970 GHz.

Unfortunately, these results also indicate that the NbTiN ground plane may have a cut-off frequency of ~ 1 THz. However, it is argued that it should be possible to extend the range of low-noise mixer operation to at least 1.12 THz by incorporating NbTiN deposition processes previously shown to produce films with $T_c \geq 16$ K [7-8]. Furthermore, it is hoped that further optimization of the device parameters will push the range of operation to at least 1.2 THz, while also improving receiver sensitivities below 1 THz.

10. ACKNOWLEDGEMENTS

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11. REFERENCES

1. A. Baryshev et al., unpublished result, 1999.
2. G. de Lange, J. J. Kuipers, T. M. Klapwijk, R. A. Panhuyzen, H. van de Stadt, and M. W. M. de Graauw, Superconducting resonator circuits at frequencies above the gap frequency, *J. Appl. Phys.* **77**, 1795-1804, 1995.
3. H. van de Stadt, A. Baryshev, P. Dieleman, Th. de Graauw, T. M. Klapwijk, S. Kovtonyuk, G. de Lange, I. Lapitskaya, J. Mees, R. A. Panhuyzen, G. Prokopenko, and H. Schaeffer, A 1 THz Nb SIS heterodyne mixer with normal metal tuning structure, *Proc. of the 6th Int. Symp. on Space THz Technology*, CIT, PC, 66-77, 1995.
4. M. Bin, M. C. Gaidis, J. Zmuidzinas, T. G. Phillips, and H. G. LeDuc, Low-noise 1 THz niobium superconducting tunnel junction mixer with a normal metal tuning circuit, *Appl. Phys. Lett.* **68**, 1714-1716, 1996.
5. P. Dieleman, T. M. Klapwijk, J. R. Gao, and H. van de Stadt, Analysis of Nb superconducting-insulator-superconducting tunnel junctions with Al striplines for THz radiation detection, *IEEE Trans. on Appl. Supercond.* **7**, 2566-2569, 1997.
6. P. Dieleman and T. M. Klapwijk, Shot noise beyond the Tucker theory in niobium tunnel junction mixers, *Appl. Phys. Lett.***72**, 1653-5, 1998.
7. R. di Leo, A. Nigro, G. Nobile, and R. Vaglio, Niobium-titanium nitride thin films for superconducting rf accelerator cavities, *J. Low Temp. Phys.* **78**, 41, 1990.
8. J. A. Stern, B. Bumble, H. G. LeDuc, J. W. Kooi, and J. Zmuidzinas, Fabrication and dc-characterization of NbTiN based SIS mixers for use between 600 and 1200 GHz, *Proc. of the 9th Int. Symp. on Space THz Technology*, CIT, PC, 305-313, 1998.
9. J. W. Kooi, J. A. Stern, G. Chattodpadyay, H. G. LeDuc, B. Bumble, and J. Zmuidzinas, Low-loss NbTiN films for THz SIS mixer tuning circuits, *Int. J. of IR and MM Waves* **19**, 373-383, 1998.

10. N. N. Iosad, B. D. Jackson, T. M. Klapwijk, S. N. Polyakov, P. N. Dmitriev, and J. R. Gao, Optimization of rf- and dc-sputtered NbTiN films for integration with Nb-based SIS junctions, *IEEE Trans. on Appl. Supercond.* **9**, 1716-1719, 1999.
11. B. D. Jackson, N. N. Iosad, B. Leone, J. R. Gao, T. M. Klapwijk, W. M. Laauwen, G. de Lange, and H. van de Stadt, DC and terahertz response in Nb SIS mixers with NbTiN striplines, *Proc. of the 10th Int. Symp. on Space THz Technology*, U. of Virginia, Charlottesville, Virginia, 144-156, 1999.
12. J. Kawamura, J. Chen, D. Miller, J. Kooi, J. Zmuidzinas, B. Bumble, H. G. LeDuc, and J. A. Stern, Low-noise submillimeter-wave NbTiN superconducting tunnel junction mixers, *Appl. Phys. Lett.* **75**, 4013-4015, 1999.
13. A. Baryshev, B. D. Jackson, G. de Lange, S. V. Shitov, J. R. Gao, N. N. Iosad, and T. M. Klapwijk, Quasi-optical terahertz SIS mixers, *these proceedings*.
14. J. R. Gao, S. Kovtonyuk, J. B. M. Jegers, P. Dieleman, T. M. Klapwijk, and H. van de Stadt, Fabrication of Nb-SIS mixers with UHV evaporated Al striplines, *Proc. of the 7th Int. Symp. on Space THz Technology*, CIT, PC, 538-548, 1996.
15. N. N. Iosad, B. D. Jackson, F. Ferro, J. R. Gao, S. N. Polyakov, P. N. Dmitriev, and T. M. Klapwijk, Source optimization for magnetron sputter-deposition of NbTiN tuning elements for SIS THz detectors, *Supercond. Sci. and Technol.* **12**, 736-740, 1999.
16. B. Leone, B. D. Jackson, J. R. Gao, and T. M. Klapwijk, Geometric heat trapping in niobium superconductor-insulator-superconductor mixers due to niobium titanium nitride leads, *Appl. Phys. Lett.* **76**, 780-782, 2000.
17. A. Skalare, *Internat. J. of Infrared and Millimeter Waves* **10**, 1339, 1989.
18. J. R. Tucker and M. J. Feldman, Quantum detection at millimeter wavelengths, *Rev. of Mod. Phys.* **57**, 1055, 1985.
19. P. Dieleman, H. G. Bukkems, T. M. Klapwijk, M. Schike, and K. H. Gundlach, Observation of Andreev reflection enhanced shot noise, *Phys. Rev. Lett.* **79**, 3486-3489, 1997.
20. B. Bumble, H. G. LeDuc, and J. A. Stern, Fabrication of Nb/Al-Nx/NbTiN junctions for SIS mixer applications above 1 THz, *Proc. of the 9th Int. Symp. on Space THz Technology*, CIT, PC, 295-304, 1998.
21. J. Kawamura, D. Miller, J. Chen, J. Zmuidzinas, B. Bumble, H. G. LeDuc, and J. A. Stern, Very high-current-density Nb/AlN/Nb tunnel junctions for low-noise submillimeter mixers, *App. Phys. Lett.* **76**, 2119, 2000.