THz SIS Mixer Development for HIFI

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ABSTRACT

Low-noise THz SIS mixers are needed for the Heterodyne Instrument for the Far-Infrared (HIFI). Based upon the success of past work, in which NbTiN/SiO_2/Al tuning circuits were shown to enable the development of low-noise SIS mixers for frequencies up to 1 THz, a new waveguide mixer design is shown to be suitable for use in the 800-960 GHz band of HIFI. Potential modifications to this design that could improve its performance at higher frequencies are also discussed.

1. INTRODUCTION

The Heterodyne Instrument for the Far-Infrared (HIFI) [1] requires low-noise SIS mixers for frequencies between 480 and 1250 GHz. Below 700 GHz, the low-loss performance of Nb tuning circuits enables the development of SIS mixers with nearly quantum-limited sensitivities [2-4]. However, the RF losses in Nb increase significantly at higher frequencies [5], causing all-Nb SIS mixers to become increasingly less sensitive [6]. Past work has shown that the use of NbTiN-based tuning circuits can yield low-noise SIS mixers at frequencies up to at least 1 THz [7-9].[1] In particular, a quasi-optical mixer incorporating a NbTiN/SiO_2/Al tuning circuit and standard Nb SIS junctions has been shown to yield a receiver sensitivity of $T_{N,rec}$ = 253-315 K between 850 and 980 GHz [8]. Unfortunately, although previously demonstrated waveguide mixers offered similar peak sensitivities [9], their RF bandwidths were significantly smaller than that of the quasi-optical mixer. Furthermore, both types of mixer showed a loss of sensitivity above 1 THz, which was attributed to increasing RF losses in their NbTiN ground planes [8,9].

This paper presents a redesigned waveguide mixer incorporating a NbTiN/SiO_2/Al tuning circuit that is similar to that used previously. This mixer is shown to yield low-noise performance over a wide RF bandwidth, making it suitable for use in the 800-960 GHz band of the HIFI instrument. Potential design improvements are also discussed.

2. MIXER DESIGN

SRON is responsible for developing SIS mixers for bands 3 and 4 of HIFI (covering 800-960 and 960-1120 GHz, respectively). The design of these mixers is expected to fulfill a long list of optical, mechanical, thermal, and electrical interface requirements, plus requirements related to space qualification. A prototype of the band 4 mixer is seen in Fig. 1, and its design is described in detail elsewhere in these proceedings [10].

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[1] Throughout this paper, NbTiN is used to represent $(Nb_{0.70}Ti_{0.30})_xN_{1-x}$, where x ~ 0.5.

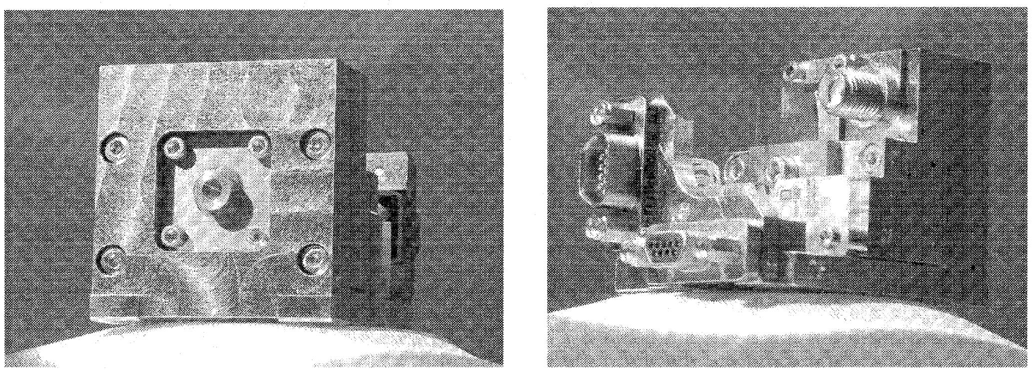


Fig. 1 – The demonstration model of the HIFI Band 4 Mixer Unit. The corrugated horn, plus the DC and IF connectors are all visible. The mixer unit is 32x32x45 mm^3.

The performance requirements for the HIFI mixers are derived from the baseline instrument sensitivity defined in the HIFI proposal (see [1]), resulting in a baseline mixer sensitivity requirement of $T_{N,mix} \sim 3.5\ hf/k_B$ across the mixers' full RF and IF bandwidths (4-8 GHz).[2] Based upon the results of past work [8,9], it is known that NbTiN/SiO_2/Al tuning circuits can yield mixers with high sensitivities up to at least 1 THz. However, the RF bandwidth of the previously demonstrated waveguide mixers was limited to ~ 100 GHz [9], due to the fact that the mixers' RF design had not been optimized. Instead, use was made of an existing full-height 1 THz waveguide mixer block and RF embedding circuit design (i.e. the designs of the waveguide probe and RF choke filter on the SIS chip) [11]. Furthermore, because the devices' on-chip tuning circuits were originally designed for use with an all-NbTiN tuning circuit, they were also non-optimal for the NbTiN/SiO_2/Al tuning circuit that was ultimately used.

The redesigned mixer incorporates a half-height waveguide, in place of the full-height waveguide used previously. The detailed waveguide, waveguide probe, and RF choke designs are all scaled from the design of a 600-700 GHz mixer that is in use at the James Clerk Maxwell Telescope (JCMT), in Hawaii [12]. In particular, the design of the JCMT mixer was scaled to the 880 and 1040 GHz centre frequencies of bands 3 and 4 of HIFI

	JCMT Mixer (650 GHz)	HIFI Band 3 (880 GHz)	HIFI Band 4 (1040 GHz)
Waveguide	400x100	296x74	248x62
Backshort Depth	140	103	88
Substrate Channel	100x70	74x52	62x42
Substrate	75x42	55x32	47x26

Note: all dimensions are given in μm.

Fig. 2 – Waveguide and substrate geometries for the mixers described here.

[2] Note that $T_{N,mix}$ is defined as the effective input noise temperature of the mixer plus a 4-8 GHz IF amplifier chain (with $T_{N,IF}$ = 10 K). It is estimated from the measured receiver noise by correcting for the RF losses in the receiver optics (i.e. beamsplitter, dewar window, and heat-filter(s)).

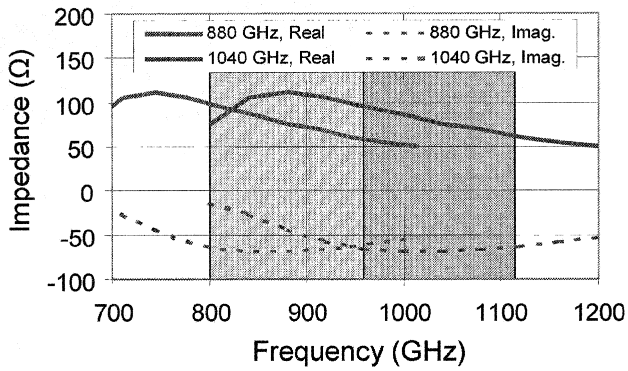
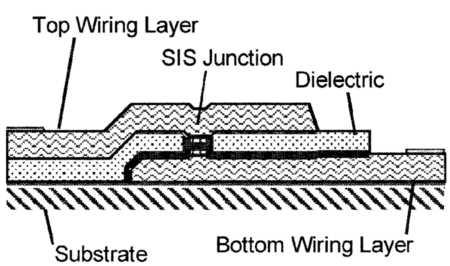


Fig. 3 – RF embedding impedances estimated for the 880 and 1040 GHz mixer designs. These are scaled from the calculated embedding impedance of the original 650 GHz design [13].

by assuming a 650 GHz centre frequency for the original design. The RF performance of the 650 GHz design was modelled in a 3-D electromagnetic simulator [13], to determine the RF embedding impedance seen at the input to the on-chip μ-strip tuning circuit. This frequency-dependent impedance was then scaled to estimate the embedding impedances of the 880 and 1040 GHz mixer designs (see Fig. 3).

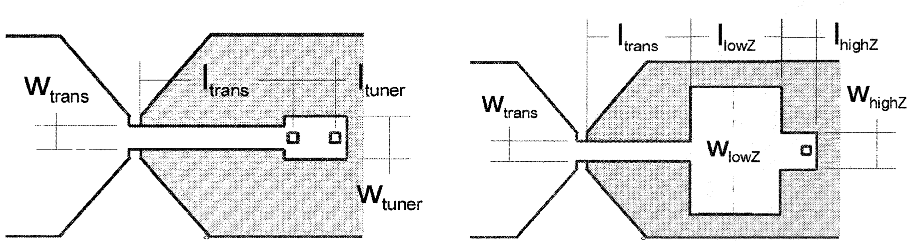
The second stage of the mixer redesign was an optimization of the on-chip tuning circuit to maximize the RF coupling to the SIS junction(s) across the 800-960 and 960-1120 GHz bands. For the purposes of this design, two basic device geometries were used – a



(a)

	Material	Critical Parameters
Substrate	fused quartz	200 μm thick polished to 20-30 μm
Ground Plane	NbTiN	300 nm T_c= 14.4 K $\rho_{n,\,16\,K}$ = 110 μΩ·cm
Dielectric	SiO_2	250 nm ε_r = 3.8
Wiring Layer	Al (+ Nb)	400 nm $\rho_{n,\,4\,K}$ = 0.4 μΩ·cm
Junction	Nb/Al-AlO_x/Nb	J_c = 7.5 kA/cm^2 A ~ 0.9 μm^2

(b)



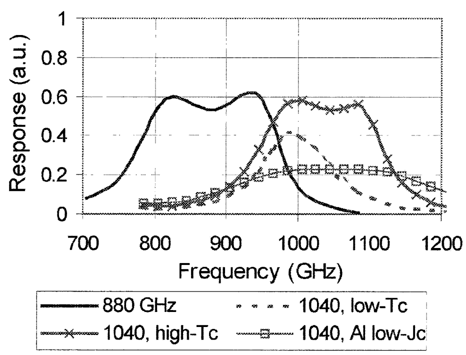
(c) (d)

Fig. 4 – SIS Device Geometry. (a) a cross-section of a single-junction device, (b) the SIS device layer properties, (c) the twin-junction tuning circuit geometry, and (d) the single-junction tuning circuit geometry.

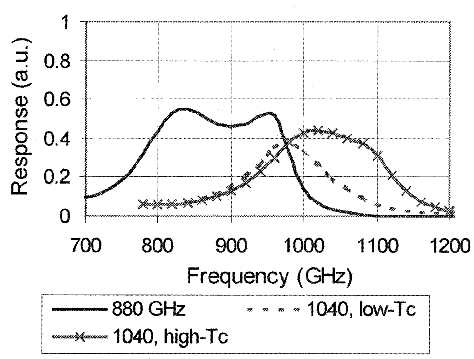
twin-junction design similar to that used previously at 1 THz [9], and a single-junction design that is similar to that in the 650 GHz JCMT mixer [12] (see Fig. 4 for schematic drawings of these tuning circuit layouts). Fig. 4 also summarizes the properties of the SIS junctions and the tuning circuit materials used for this design study.

For both basic device geometries, the coupling of radiation to the SIS junction(s) has been estimated by using the embedding impedances in Fig. 3 as the source impedance in a simple transmission line model of the μ-strip tuning circuit and a lumped element model of the SIS junction(s). In this model, the surface impedance of the Al wiring layer is calculated under the assumption that the Al is in the anomalous limit [14], while the surface impedance of the NbTiN ground plane is calculated using the Mattis-Bardeen formulation for the complex conductivity of a superconductor in the extreme anomalous limit [5] (using values of $T_c = 13.0$ and 14.5 K to model effective gap frequencies of 1.0 and 1.1 THz, respectively). The results of these calculations are summarized in Fig. 5 for the four basic designs (880 and 1040 GHz variants of the twin- and single-junction designs).

As seen in Fig. 5, the calculated responses of both the twin- and the single-junction designs can cover the full 800-960 GHz band, although the coupling the junction(s) is expected to be 20-30 % higher if a twin-junction design is used. In contrast, the performance of the 1040 GHz designs is critically dependent upon the effective gap frequency of the NbTiN ground plane (as simulated by the use of different values of the T_c of NbTiN). In particular, if the effective gap of the NbTiN is 1.1 THz, the 1040 GHz designs are expected to behave similarly to the 880 GHz designs. If, on the other hand, the effective gap of the NbTiN is ~ 1.0 THz (as was found to be the case in previous work [8,9]), the calculated performance of both designs drops significantly across the 960-1120 GHz band. In this case, an all-normal-metal tuning circuit would be needed to obtain significant sensitivity near the upper end of the band (see Fig. 5b).



(a)



(b)

Fig. 5 – Calculated RF coupling to the SIS junction(s) for the 880 and 1040 GHz twin-junction and single-junction designs (in (a) and (b), respectively). The twin-junction designs are estimated to be ~ 20-30 % more sensitive than the single-junction designs, while the responses of both types of 1040 GHz device depend strongly upon the T_c of the NbTiN ground plane (modelled by using different values of the T_c of the NbTiN ground plane).

3. DEVICE FABRICATION AND CHARACTERIZATION

Based on the results of the design study described in the previous section, three of the four basic device designs have been implemented in finished devices (twin- and single-junction 880 GHz devices, plus twin-junction 1040 GHz devices).

The fabrication process used to produce these devices is similar to that used previously for the fabrication of NbTiN-based SIS devices [9,15]. The NbTiN ground plane is deposited at room temperature, yielding a film with $T_c = 14.4$ K and $\rho_n \sim 110\ \mu\Omega\cdot$cm [16]. The most significant modifications to the process described in Refs. 9 and 15 are in the definition of the SIS junctions – reactive ion etching of the Nb junction electrodes in $CF_4 + O_2$ has been replaced by reactive ion etching in $SF_6 + O_2$, and an extra O_2 plasma etch has been added to controllably shrink the resist pattern following the etching of the upper Nb electrode (prior to the Ar sputter etch of the junction barrier). These changes are intended to improve the reliability of the junction definition process.

After fabrication is complete, the devices are evaluated by first measuring their DC current-voltage characteristics (at 4.2 K) to identify promising candidates for RF testing. Selected devices are then mounted in a reduced-height mixer block, together with the appropriate corrugated horn, and the mixer block is mounted on the cold plate of a Helium cryostat. RF radiation is coupled into the cryostat through a 100-μm Mylar vacuum window and Zitex G104 infrared heat-filters mounted on the 77 and 4 K stages of the cryostat. The quasi-optical RF beam is focussed into the mixer by an off-axis elliptical mirror that is mounted on the 4 K stage of the cryostat. The 4-8 GHz IF output from the junction is decoupled from the DC bias with a planar bias-T circuit that is built into the mixer block. The mixer's IF output then passes through a 4-8 GHz Pamtech isolator and a low-noise 4-8 GHz YEBES amplifier [17] before leaving the cryostat. The total noise of the IF chain is ~ 10 K across the 4-8 GHz band.

The spectral response of the mixer is first measured with a Fourier transform spectrometer while operating the device as a direct-detector. Testing then proceeds with measurements of the heterodyne sensitivity of the receiver. For the results presented here, the response of the mixer is evaluated in a total power mode by measuring the full 4-8 GHz output of the receiver with a power meter. The noise and gain of the receiver, plus the noise contributions of the receiver optics, are evaluated using the Callen-Welton formulation for the signal power radiated by a blackbody load [18].

4. MEASURED DEVICE PERFORMANCE

The DC current-voltage characteristic of a representative 880 GHz twin-junction device is seen in Fig. 6, together with the IF output power of the device (both with and without the application of local oscillator power). The gap voltage of these devices is typically 2.6-2.8 mV and the sub-gap to normal-state resistance ratio is typically 10-15. (This is lower than is expected for 7-8 kA/cm^2 Nb SIS junctions, but is comparable to previous results obtained using Nb junctions integrated with NbTiN-based tuning circuits [8,9].)

As a test of the frequency-responses of the three basic tuning circuit designs, devices of each type have been tested with the Fourier transform spectrometer (see Fig. 7). As can be seen, both the single- and twin-junction 880 GHz designs yield strong responses across a wide RF bandwidth. In contrast, the responses of the 1040 GHz devices are

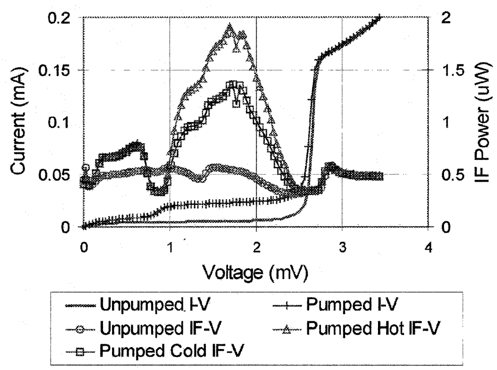
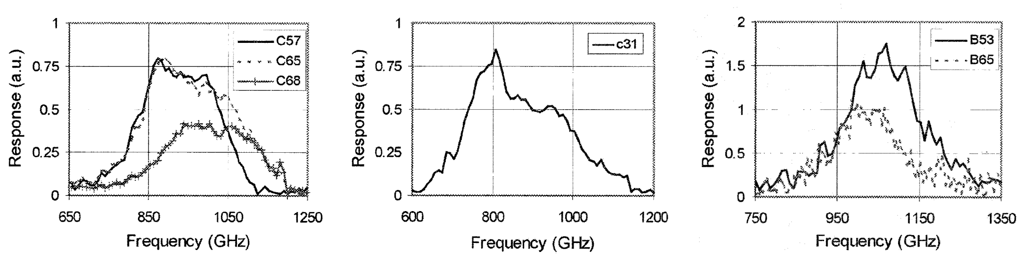


Fig. 6 – Current and IF output power vs. bias voltage for an 880 GHz twin-junction device measured at 4.5 K, both with and without applying 866 GHz LO power. The hot and cold IF output power curves correspond to 300 and 77 K blackbody signal loads and the sensitivity of this mixer is determined to be $T_{N,rec}$ = 420 K at 866 GHz.

much weaker than those of the 880 GHz devices. This is attributed to the fact that the response peaks of the 1040 GHz devices are tuned too high in frequency, so that their sensitivity is reduced by losses in the NbTiN ground plane above 1 THz. Evidence of this cut-off is also seen in the responses of the 880 GHz twin-junction devices, which are shifted above the 800-960 GHz band in which they are designed to operate. (They are actually sensitive from 850 to 1000-1050 GHz.)

The heterodyne responses of the four 880 GHz devices in Fig. 7 are summarized in Fig. 8. The twin-junction devices are seen to yield low receiver noise across the 850-970 GHz band, with optimum receiver sensitivities of 420 and 364 K measured at 4.5 and 2.5 K, respectively. Also shown in Fig. 8 are estimates of the effective input noise at the mouth of the waveguide horn (obtained by correcting for the estimated losses in the input optics). After this correction is applied, these mixers are found to offer sensitivities at

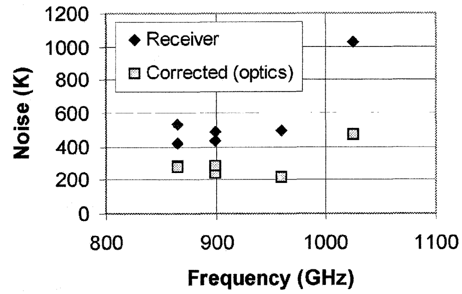


(a) (b) (c)

Fig. 7 – Measured FTS responses of: (a) three 880 GHz twin-junction devices, (b) one 880 GHz single-junction device, (c) and two 1040 GHz twin-junction devices. Both 880 GHz designs produce strong responses over a broad RF bandwidth. In contrast, the 1040 GHz devices produce very weak responses. The poor performance of the 1040 GHz devices is attributed to the fact that the devices' centre frequencies are tuned above the effective gap frequency of the NbTiN ground plane.

Chip	Design	Temp. (K)	Freq. (GHz)	$T_{N,rec}$ (K)	$T_{N,mix}$ (K)
c31	single	4.5	805	637	452
		2.5	805	506	351
c57	twin	4.5	866	420	284
c65	twin	4.5	890	440	293
		2.5	894	364	232
c68	twin	4.5	952	1260	430

(a)



(b)

Fig. 8 – Measured receiver noise temperatures of the 880 GHz devices measured to-date (together with receiver noise temperatures that have been corrected for optical losses). (a) summarizes the peak performance of the four measured devices (note that the twin-junction devices, c57 and c65, are significantly more sensitive than the single-junction device, c31, as predicted in Fig. 5), while (b) summarizes the frequency dependence of the heterodyne response of c57 at a 4.5 K bath temperature. All noise temperatures are averaged over the full 4-8 GHz IF band.

2.5 K of $T_{N,mix} \sim 230$ K. Finally, with a peak sensitivity of $T_{N,rec} = 506$ K at 2.5 K, the one single-junction device measured to-date is ~ 30 % less-sensitive than the most sensitive twin-junction device, which is in line with the predictions of the tuning circuit performance presented in Fig. 5.

5. DISCUSSION

Based upon these results, it appears that the 880 GHz twin-junction device design performs as expected, yielding relatively low noise across a broad RF bandwidth. In particular, the measured sensitivity of $T_{N,mix} \sim 230$ K at 890 GHz approaches the baseline specification for the HIFI mixers (~ 170 K at this frequency). However, although some incremental improvements may be possible within the existing design and device geometry (i.e. if junctions with lower leakage currents and/or higher current-density (J_c) can be obtained, or if the resistivity of the Al wiring layer can be reduced), an improvement beyond this baseline would likely require a more major design modification. In particular, two potentially major changes can be identified:

A. The use of high-quality, high current-density junctions with AlN_x barriers [19,20] would reduce the loss in the $NbTiN/SiO_2/Al$ tuning circuit [21] (which is estimated to be ~ 3 dB in the present twin-junction devices). See Fig. 9a for an estimate of the RF coupling improvement that could be obtained by using junctions with $J_c = 20$ kA/cm^2, in place of the 7.5 kA/cm^2 used currently.

B. Alternatively, the present waveguide + waveguide probe + RF-choke design yields a relatively large embedding impedance (see Fig. 3), which requires a high-Q tuning circuit to couple radiation to the SIS junction(s). In contrast, the use of a suspended-stripline design for the RF choke [22,23] or a single-sided waveguide probe [24] could yield a lower embedding impedance, and thereby reduce the RF loss in the tuning circuit.

More significant improvement is needed in the 1040 GHz devices, as the existing NbTiN ground plane does not appear to be of high enough quality for use at 1.1 THz. In particular, two options are seen as being the most likely to succeed:

A. Make use of the existing design and geometry, but with higher quality NbTiN films grown at elevated temperatures and/or on lattice-matched MgO substrates [25,26]. (Note that for a waveguide mixer, the elevated-temperature option is preferred because the MgO substrate would have to be thinned to ~ 15 μm to be electrically equivalent to the 25 μm thick quartz substrates used currently.)

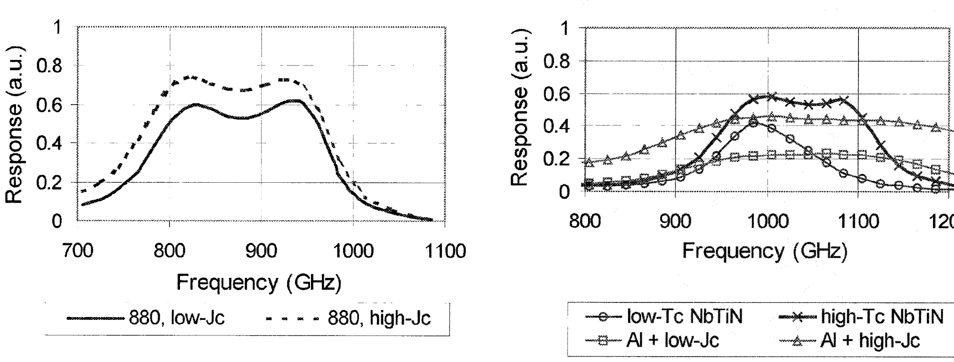
B. Alternatively, the integration of an all-normal-metal tuning circuit with high-quality, very-high J_c SIS junctions based on an AlN_x tunnel barrier has been shown to yield low-noise mixers up to at least 1.2 THz [27].

The potential improvements in RF coupling that could be obtained by these two options are demonstrated in Fig. 9b.

Unfortunately, a number of these development options are not seen as realistic within the context of the pressing HIFI schedule. (The flight model mixers are needed by mid-2003, meaning that the flight model SIS devices are needed by the end of 2002.) For this reason, it is expected that the 880 GHz mixers for HIFI will be based upon the existing design (although some incremental improvements in the devices may be possible). For the 1040 GHz devices, the most likely solution will be the use of higher-quality NbTiN films (grown at elevated temperatures) in the existing device design and production process (since even a small improvement in the effective gap of the NbTiN should be enough to significantly improve the mixer performance in the 960-1120 GHz range).

6. CONCLUSIONS

A waveguide SIS mixer incorporating a reduced-height waveguide and a twin-junction $NbTiN/SiO_2/Al$ tuning circuit is shown to yield low-noise performance over a broad RF bandwidth (850-1000 GHz), with a best-measured sensitivity of $T_{N,rec}$ = 364 K at 890 GHz. Correcting for the losses in the receiver optics, this corresponds to an input noise



(a) (b)

Fig. 9 – (a) The simulated effect of increasing the junction J_c to improve the performance of the 880 GHz design. (b) The effect of modifications to improve the performance of the 1040 GHz devices (increasing the NbTiN gap frequency, or using an all-Al tuning circuit with low- or high-J_c junctions).

of the mixer together with the IF chain of $T_{N,mix} \sim 230$ K, which is approaching the baseline specification for the HIFI instrument (170 K at this frequency). Unfortunately, the performance of this mixer geometry drops significantly above ~ 1 THz, due to increasing RF losses in the NbTiN ground plane. It is hoped that this problem can be rectified by the integration of higher-quality NbTiN films with the existing device design and production process.

7. ACKNOWLEDGEMENTS

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