Waveguide and Quasi-optical 1 THz SIS Mixers Incorporating NbTiN/SiO$_2$/Al Tuning Circuits

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ABSTRACT

The performance of 1 THz waveguide and quasi-optical mixers incorporating NbTiN/SiO$_2$/Al tuning circuits are evaluated. Both geometries yield low mixer noise temperatures up to 1 THz, with reduced sensitivities at higher frequencies. The drop in sensitivities above 1 THz is attributed to the non-ideal structure of NbTiN films grown at room-temperature, which results in significant losses in the NbTiN ground plane above 1 THz. The design and performance of the quasi-optical lens-antenna is also discussed.

1. INTRODUCTION

The Heterodyne Instrument for the Far-Infrared (HIFI) requires THz mixers with noise temperatures ($T_{N,mix}$) < 3·hv/k (i.e. < 140 K at 960 GHz). Past work has shown that Nb-based superconductor-insulator-superconductor (SIS) mixers yield quantum-limited performance below 680 GHz [1,2]. Above 700 GHz, rf losses in Nb increase [3,4], such that Al wiring is preferred to Nb above 800 GHz [5,6]. Unfortunately, the optimum sensitivity of these mixers is limited to 200-250 K at 1 THz (derived from [6] and [7]). Further improvements in THz mixer sensitivities will require reduced tuning circuit losses (5-9 dB in [6,7]). Although this may be achieved in part by the use of high current-density (high-J_c) SIS junctions [8], truly quantum-limited 1 THz mixers will require low-loss superconducting wiring layers with F_{gap} ~ 1.1 THz, or more.

The recent demonstrations of NbTiN-based SIS receivers with noise temperatures of 205 K at 798 GHz [9] and 315 K at 980 GHz [10] confirm that the use of NbTiN-based tuning circuits can yield low-noise mixers up to 1 THz. However, it remains to be shown that similar performance is attainable above 1 THz – based on $T_{c, NbTiN}$ = 14.5-15.5 K, and the measured relationship between F_{gap} and T_c in NbN (F_{gap} = 3.52-4.16·$k_B T_c$/h [11,12]),

it is predicted that NbTiN is low-loss up to 1.05-1.35 THz.

In this paper, the performance of THz waveguide and quasi-optical mixers incorporating Nb/Al-AlO$_x$/Nb SIS junctions and NbTiN/SiO$_2$/Al tuning circuits are compared and analyzed in relation to the measured low-frequency electrical properties of the NbTiN films used as a ground plane. Additionally, the antenna beam-pattern of the quasi-optical lens-antenna system is discussed.

Note that all receiver and mixer sensitivities presented here are calculated using the Callen-Welton formulation [13] for the effective temperatures of the signal loads and optical elements. Also, $T_{N,mix}$, is defined as the DSB input noise of the mixer unit, from the input of the beam-forming element (waveguide horn or quasi-optical lens) to the IF connector. It is calculated from the receiver noise by subtracting the contributions of the IF chain and receiver optics.

2. MIXER DESIGN AND FABRICATION

Waveguide mixers are produced by integrating 7.5 kA/cm^2, 1-µm^2 Nb SIS junctions with a 300-nm NbTiN ground plane, a 250-nm SiO$_2$ dielectric layer, and a 400-nm Al wiring layer (see Fig. 1). The NbTiN ground plane has $T_c \approx 14.4$ K and $\sigma_{16K} \approx 0.9 \times 10^6$ Ω^{-1}m^{-1} [14], while the sputtered Al has $\sigma_{4K} \approx 2 \times 10^8$ Ω^{-1}m^{-1}, and is expected to be in the anomalous limit [15]. 100 nm of Nb is added to the Al wiring for chemical passivation, and to reduce the series resistance of the rf-choke filter. For RF measurements, the devices are mounted in a full-height 1 THz mixer block with a diagonal horn. The waveguide mixer and its fabrication process are described in more detail in [16,17].
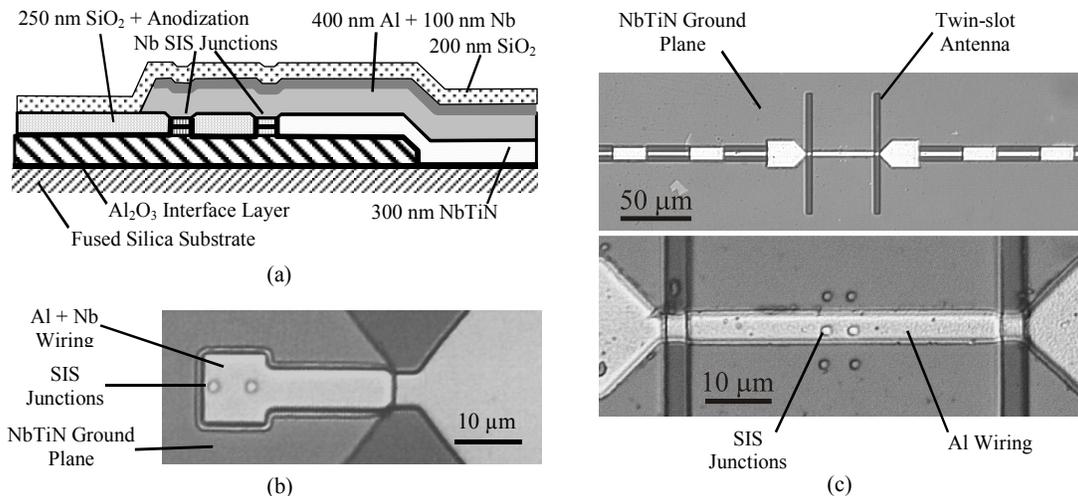

Figure 1. (a) cross-section of the NbTiN/SiO$_2$/Al tuning circuit (modified from [16]), (b) microscope image of the waveguide device geometry used here (modified from [16]), and (c) microscope images of the quasi-optical device geometry used here (modified from [10]).

Quasi-optical mixers are produced by integrating twin-slot antennas with a double-junction tuning circuit, using the same junction and layer geometry as in the waveguide mixer (note that the 100-nm Nb layer is not present on the wiring of the quasi-optical mixer). For RF measurements, the quasi-optical devices are mounted on a 10-mm elliptical Si lens. The quasi-optical mixer design is described in more detail in [10,18].

3.   RF MEASUREMENT SETUP

The quasi-optical and waveguide receivers are described in [10] and [16], respectively. The waveguide receiver includes a 100-µm Mylar window at 295 K, a Zitex G104 heat-filter at 77 K, and a high-density polyethylene lens at 4 K, while the quasi-optical receiver includes a 12-µm Kapton window at 295 K, and Zitex heat-filters at 77- and 4-K. The direct-detection response of each mixer is measured in an evacuated Michelson interferometer, while heterodyne sensitivity is determined from Y-factor measurements with 295- and 77-K loads, BWO local oscillators (LOs) operating between 830 nd 1100 GHz, and Mylar beamsplitters of 6-, 14-, and 49-µm thickness. The IF output from the mixer is cryo-amplied before being further amplified and bandpass filtered at room temperature. Using the unpumped mixers as noise sources, the noise and gain of the IF chain are determined to be 4-5 K and 68 dB in an 85 MHz band at 1.46 GHz.

4.   DIRECT-DETECTION MEASUREMENT RESULTS AND THE NBTIN CUT-OFF

The fixed-tuned direct-detection responses of four waveguide mixers and two quasi-optical mixers are shown in Fig. 2 (all at 4.6 K). Both geometries yield high sensitivities below 1 THz. However, all 4 waveguide devices, plus one of the two quasi-optical mixers, have high-frequency cut-offs at ~ 1 THz, despite having significantly different low-frequency roll-offs. This common cut-off is attributed to losses in the NbTiN ground plane at 1 THz and above.

Also shown in Fig. 2b are calculations of the predicted direct detection responses of each quasi-optical device for two possible NbTiN gap frequencies – 1080 and 970 GHz. In these calculations, the NbTiN surface impedance is calculated using the frequency-dependent resistivity of a superconductor in the anomalous limit [3]. Further details of these calculations can be found in [10]. Comparing the measured and predicted device responses, it is seen that the response of device 166 can be relatively well predicted using NbTiN gap frequencies of either 970 or 1080 GHz, but that the high-frequency response of device 162 can only be modeled using a low NbTiN gap frequency (F_{gap}) of 970 GHz.

The apparent NbTiN F_{gap} at 970 GHz is significantly lower than is expected for NbTiN with T_c = 14.4 K (1.05-1.25 THz is expected). However, recent work has shown that there are significant non-homogeneities in the properties of NbTiN films deposited at room temperature [19]. In particular, the T_c and resistivity of these films are strongly thickness-dependent (up to ~ 300-nm), and inductive measurements of T_c yield significantly larger transition widths (ΔT_c) than is observed in resistive measurements (signs of vertical and

(a)   (b)
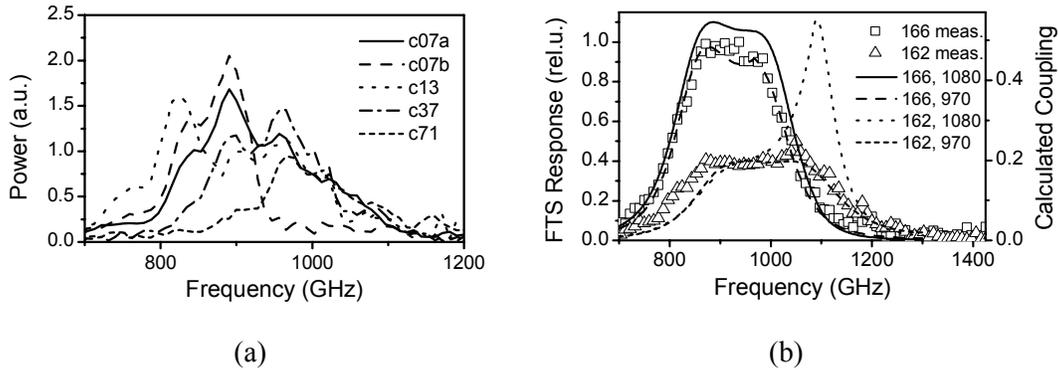
Figure 2 - (a) Measured direct-detection responses of four waveguide mixers at 4.6 K (modified from [16]). The devices have different junction sizes and separations, and different transformer lengths. (b) Measured direct-detection responses of two quasi-optical mixers at 4.6 K (modified from [10]). The two devices have different junction areas, but are otherwise identical. Also seen are calculated device sensitivities for NbTiN gap frequencies of 970 and 1080 GHz. The predicted response of device 162 matches the measured curve for $F_{gap, NbTiN}$ = 970 GHz.

lateral non-homogeneities, respectively). Thus, it is believed that the observed 970 GHz tuning circuit cut-off is due to rf losses in the NbTiN ground plane in a relatively small number of grains with particularly low values of T_c. Fortunately, this argument also implies that it should be possible to increase the cut-off frequency by using higher-quality NbTiN layers (with higher T_c and improved homogeneity), such as those deposited on MgO substrates or at elevated temperatures [19,20].

5. HETERODYNE MEASUREMENT RESULTS

The receiver noise temperatures of four waveguide and two quasi-optical mixers are shown in Fig. 3 for measurements at 4.6 and 2.8 K. In general, the measured heterodyne sensitivities and RF band-widths of these devices agree reasonably well with the direct-detection response curves seen in Fig. 2.

Using the waveguide mixers at 4.6 K, a minimum $T_{N,rec}$ of 425 K is obtained with device c07 at 895 GHz (with a 6 μm beamsplitter), while optimum sensitivity near 1 THz is obtained at 2.8 K with c37 and a 14 μm beamsplitter ($T_{N,rec}$ = 565 K and G_{rec} = -12.9 dB at 970 GHz). The 20 % improvement in the response of waveguide mixer c13 upon cooling from 4.6 to 2.8 K is typical for these mixer geometries (both waveguide and quasi-optical). Also, the sharp dip in the sensitivities of waveguide mixers c13 and c37 at 980-990 GHz is due to water vapour absorption.

Quasi-optical mixer 166 yields significantly higher receiver sensitivities than the waveguide mixers, with an optimum $T_{N,rec}$ of 253 K obtained at 850 GHz and 2.8 K. The noise of this receiver rises slowly approaching 1 THz (315 K at 980 GHz), with a sharp rise in $T_{N,rec}$ at 1 THz (to 405 K at 1015 GHz). Mixer 162 is significantly less sensitive

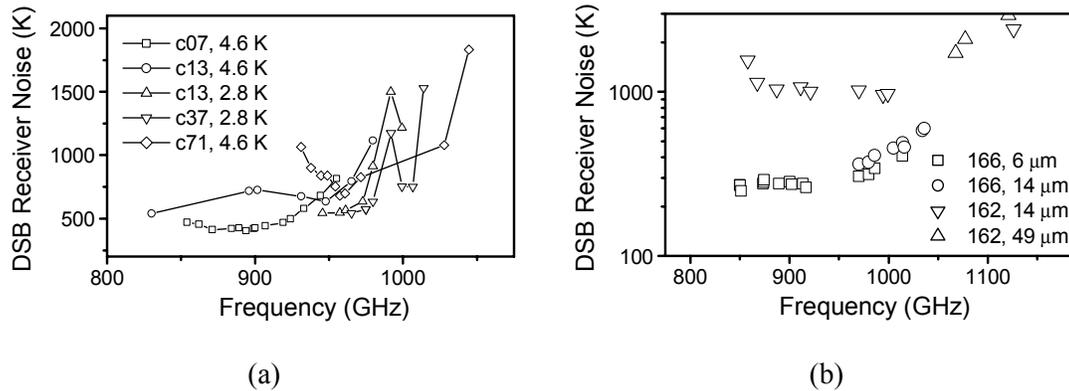(a)   (b)

Figure 3 - (a) Measured $T_{N,rec}$ for 4 waveguide devices measured at 4.6 K (c07, c13, and c71) and 2.8 K (c13 and c37). c13, c37, and c71 are measured with a 14-µm beamsplitter, while c07 is measured with a 6-µm beamsplitter (modified from [16]). (b) $T_{N,rec}$ of 2 quasi-optical mixers measured at 2.8 K with 6-, 14-, and 49-µm beamsplitters (modified from [10]).

than device 166, but it does demonstrate reasonable performance up to much higher frequencies ($T_{N,rec}$ ~ 2200 K at 1120 GHz).

6. RECEIVER SENSITIVITY ANALYSIS

Focusing on the devices with the highest THz sensitivities (waveguide device c37 at 970 GHz and quasi-optical device 166 at 980 GHz, both at 2.8 K), the measured receiver sensitivities are analyzed to estimate the rf loss in the NbTiN ground plane, and to compare the sensitivities of the two mixer geometries. The details of these calculations are contained in [10] and [16], with the results summarized here in Table I.

From this analysis, it is seen that the loss in the NbTiN ground plane is relatively low up to 970 GHz (< 0.6 dB), in both mixer geometries. Additionally, the significantly higher receiver sensitivity obtained with the quasi-optical mixer is found to be

Table I

Receiver noise breakdown and corrected mixer unit sensitivities of
waveguide device c37 [16] and quasi-optical mixer 166 [10]

Device	$T_{N,rec}$ G_{rec}	$T_{N,opt}$ G_{opt}	G_{Tucker}	G_{tuning}	G_{Al}	G_{NbTiN}	$T_{N,mix}$ G_{mix}
WG c37 (970 GHz, 2.8 K)	563 - 12.9	146 - 2.5	- 7.2	- 3.2	- 2.5-3	- 0.2-0.7	182 - 10.4
QO 166 (980 GHz, 2.8 K)	315 - 11.1	35 - 1.2	- 7.2	- 2.7	- 2.3	- 0-0.4	171 - 9.9

All gains are in dB, while noise temperatures are Callen-Welton values, and are given in K.
G_{Tucker} is the DSB conversion gain of the SIS junctions, and -G_{tuning} is the estimated tuning circuit loss, which is divided into -G_{Al}, the loss in the Al, and -G_{NbTiN}, the loss in the NbTiN.
$T_{N,mix}$ and G_{mix} are the effective input noise temperatures and DSB gains of the mixer units.

attributable to the lower optical losses in the quasi-optical receiver – the effective sensitivities of the two mixer geometries are similar ($T_{N,mix}$ = 170-180 K). Furthermore, although additional work is needed to further improve mixer sensitivities (especially above 1 THz), it is noted that these values of $T_{N,mix}$ are already within ~ 30 % of the HIFI goal at these frequencies.

Although the peak sensitivities of the two mixer geometries are similar, it is important to note that the quasi-optical mixers have significantly larger RF band-widths than the waveguide mixers. In particular, quasi-optical mixer 166 yields high sensitivity over most of HIFI mixer band 3 (800-960 GHz), while the waveguide mixers typically have 3-dB band-widths of 100-150 GHz, which is much too narrow for use in HIFI. The narrow band-widths obtained with the waveguide mixers is the result of them having a less-mature RF design relative to that of the quasi-optical mixer (the combined design of the waveguide, waveguide probe, RF choke filters and NbTiN/SiO$_2$/Al tuning circuit has not been optimized yet). An optimized design, incorporating a reduced-height waveguide [21] should yield much larger RF band-widths than those observed here.

7.   QUASI-OPTICAL MIXER BEAM-PATTERN MEASUREMENT SET-UP

The far-field antenna beam-pattern of the quasi-optical mixers is measured in direct-detection using a 2-D rotational setup [18]. In this measurement, a chopped local oscillator is used to pump the mixer while the mixer is rotated around its waist. The junction is biased at ~ 2.4 mV (just below its gap) and the detected signal (current) is measured with a lock-in amplifier. The signal-to-noise ratio at the peak of the co-polar beam pattern is at least 30-dB in this setup (limited by the dynamic range of the lock-in).

Co- and cross-polar beam patterns are obtained using two polarizing grids located near the output of the local oscillator. (Two grids are used to ensure that the incident power is equal in the co- and cross-polar measurements.)

Note that the LO is placed 50-100 cm from the mixer to ensure that the LO beam at the input to the mixer is large relative to offsets in the mixer's beam waist that may occur if the center-of-rotation is slightly misaligned relative to the beam waist location. The spreading of the LO beam also ensures that the power incident on the mixer is low enough to maintain the linearity of the photon-assisted tunneling response of the device.

Differences between the direct-detection and heterodyne beam-patterns of this mixer have not been quantified at this time.

8.   MEASURED AND CALCULATED ANTENNA BEAM-PATTERNS

2-dimensional co- and cross-polar beam patterns of the quasi-optical mixer (at 940 GHz) are presented in Fig. 4a and 4b, while 1-dimensional E- and H-plane cuts of the co-polar pattern (at 920 GHz) are presented in Fig. 4c and 4d. Fig. 4c and 4d also include theoretical antenna beam patterns calculated using [22] for two cases: (1) the antenna is
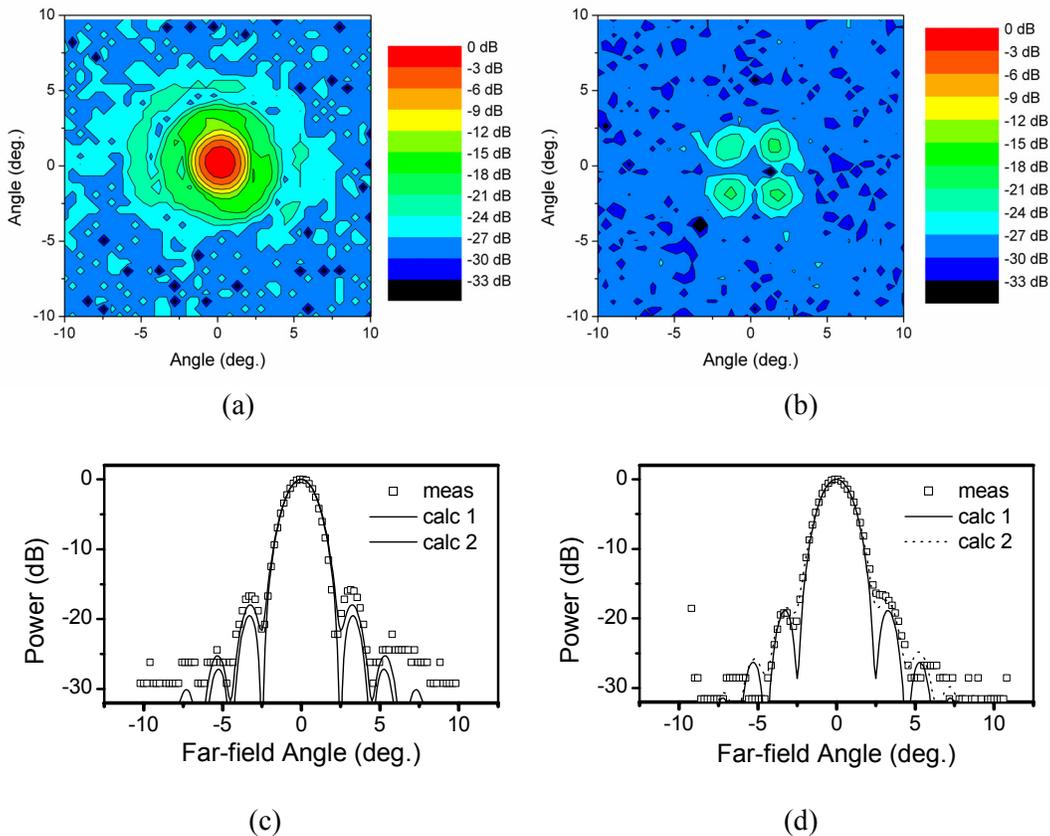
Figure 4 – Antenna beam patterns of a 950 GHz twin-slot antenna mounted on a 10-mm elliptical Si lens. (a) measured 2-D co-polar pattern at 940 GHz, (b) measured cross-polar pattern at 940 GHz, (c) overlay of measured and calculated [22] E-plane cuts of the co-polar pattern in at 920 GHz, and (d) measured and calculated [22] H-plane cuts of the co-polar pattern at 920 GHz..

perfectly aligned to the back focus of the lens; and (2) the antenna is offset 20 μm along the length of the antenna slots and 40 μm behind the back focus of the lens.

Examining the 1-dimensional beam patterns in Fig. 4c and 4d, it is seen that the measured beam-widths are relatively well predicted by theory, with a slight improvement in the agreement if the antenna is assumed to be offset from the focus of the lens. Similar comparisons have been performed at 815, 860, and 1025 GHz, yielding similar agreement between measurement and theory, as summarized in Table II. These calculations are also found to relatively accurately predict the side-lobe levels in the co-polar beam-patterns – the measured side-lobes are ~ 15-18 dB below the main peak, and the predictions typically agree with the measurements to within 2-3 dB. Note that the asymmetry in the measured H-plane beam-pattern (Fig. 4d) may be due to a slight offset of the antenna with respect to the focus of the lens.

The cross-polar beam pattern measured at 940 GHz (Fig. 4b) is similar to those obtained at 812 and 1020 GHz, with four peaks located symmetrically around the co-

TABLE II

Measured and calculated [22] far-field E- and H-plane –10 dB beam-widths of
a 950 GHz twin-slot antenna with a 10-mm Si elliptical lens

Frequency (GHz)	$\theta_{E,meas}$	$\theta_{E,calc\ 1}$	$\theta_{E,calc\ 2}$	$\theta_{H,meas}$	$\theta_{H,calc\ 1}$	$\theta_{H,calc\ 2}$
812	3.95	3.8	3.9	4.12	3.9	4.0
860	3.85	3.6	3.6	3.98	3.6	3.8
920	3.4	3.5	3.5	3.7	3.5	3.6
1025	3.25	3.3	3.3	3.65	3.1	3.4

All beam-widths are the far-field angle in degrees.

polar main beam (~ 22-23 dB below the co-polar peak). This general shape is in good agreement with calculations [22], although the peaks are 2-3 dB higher than expected. Note that the quality of the polarizing grids used is demonstrated by the 27-30 dB suppression of the co-polar main lobe in the cross-polar beam pattern.

9. QUASI-OPTICAL LENS DESIGN FOR HIFI

Quasi-optical mixers typically incorporate either the elliptical lens used in this work, or a hyper-hemispherical lens. Unfortunately, these two lens designs produce antenna beam-patterns with relatively extreme far-field divergence angles – the hyper-hemisphere produces a highly divergent beam ($\theta_{-10\ dB}$ ~ 25°), while the ellipse produces a highly collimated beam ($\theta_{-10\ dB} \approx 110\cdot\lambda/D$ ~ 3.5° for a 10-mm lens at 920 GHz). The extreme nature of these beam divergences can complicate the integration of a quasi-optical mixer into a complex optical system. For example, the design of the HIFI focal plane system would be simplified by the use of quasi-optical mixers with a relatively moderate beam divergence angle. This would allow the beam-shaping optics in front of a quasi-optical mixer to be similar to those used for a waveguide mixer with a corrugated horn (the horns in HIFI will produce a beam divergence angle of $\theta_{-10\ dB}$ ~ 18°).

It is possible to reduce the far-field divergence angle of the beam produced by a hyper-hemispherical lens by increasing the lens extension length [23], forming an extended-hemispherical lens. However, this method introduces large phase errors to off-axis rays, yielding an aberrated beam-pattern. For this reason, it would be preferable to modify both the surface shape and the extension length to obtain a design that produces the desired beam divergence angle, while also minimizing optical aberrations. The detailed design of this lens is currently in progress.

10. CONCLUSIONS

Waveguide SIS mixers incorporating Nb tunnel junctions and NbTiN/SiO$_2$/Al tuning circuits $T_{N,rec}$ = 565 K at 970 GHz. Using improved receiver optics, quasi-optical mixers with a similar tuning circuit yield $T_{N,rec}$ = 315 K at 980 GHz. Analyzing the noise and

gain of these receivers, it is shown that the intrinsic sensitivities of these mixers are similar near 1 THz ($T_{N,mix}$ ~ 170-180 K at 970-980 GHz), and that the loss in the NbTiN ground plane is relatively low (< 0.6 dB) up to 980 GHz. Receiver sensitivities are seen to drop above 1 THz, due to increasing loss in the NbTiN ground plane due to rf absorption in a relatively small concentration of NbTiN grains with T_c's that are significantly lower than that measured for a relatively large 300-nm thick film.

Measured antenna beam-patterns for a quasi-optical mixer with a twin-slot antenna mounted on a 10-mm elliptical Si lens are shown to be in relatively good agreement with theoretical predictions. The ongoing optimization of the quasi-optical lens-antenna for integration into the HIFI optical system is also discussed.

ACKNOWLEDGMENT

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