IEEE TRANSACTIONS ON APPLIED SUPERCONDUCTIVITY, VOL. 11, NO. 1, MARCH 2001

NbTiN/SiO$_2$/Al Tuning Circuits for Low-Noise 1 THz SIS Mixers

B. D. Jackson, N. N. Iosad, G. de Lange, A. M. Baryshev, W. M. Laauwen, J.-R. Gao, and
T. M. Klapwijk

***Abstract*—Waveguide SIS mixers in which Nb/Al-AlO$_x$/Nb tunnel junctions are integrated with NbTiN/SiO$_2$/Al tuning circuits are shown to yield receiver noise temperatures as low as 565 K at 970 GHz. Analyzing the noise and gain of one such receiver, it is shown that the NbTiN ground plane is low-loss (< 0.6 dB) at 970 GHz. These results are in good agreement with results obtained previously with a quasi-optical mixer incorporating a similar tuning circuit. A decrease in sensitivity above 1 THz is attributed to increasing loss in the NbTiN.**

***Index Terms*—Mixers, submillimeter-wave devices, superconducting devices, radio astronomy.**

I. INTRODUCTION

THE Heterodyne Instrument for the Far-Infrared Space Telescope (FIRST) requires THz mixers with noise temperatures, $T_{N,mix}$[1], lower than $3 \cdot hv/k$ (i.e. < 150 K at 960 GHz). Past work has shown that superconductor-insulator-superconductor (SIS) mixers incorporating Nb/Al-AlO$_x$/Nb tunnel junctions and tuning circuits can have quantum-limited sensitivities below the superconducting gap frequency of Nb ($F_{gap} = 2 \cdot \Delta/h$ = 680 GHz) [1],[2]. Above 700 GHz, rf losses in Nb increase significantly [3],[4], and Al wiring layers are preferred to Nb above 800 GHz [5],[6]. However, the optimum noise of these mixers is limited to 200-250 K at 1 THz (derived from data in [6] and [7]).

Further improvements in THz receiver sensitivities will likely require a significant reduction in tuning circuit losses (5 to 9 dB in [5] and [6]). This may be partially achieved by improving the quality of high-current-density (high-J_c) SIS junctions — increasing J_c reduces the tuning circuit quality factor needed to tune out the junction capacitance. However, the development of truly quantum-limited 1 THz receivers is expected to ultimately require low-loss superconducting wiring layers with $F_{gap} \approx 1.1$ THz, or more. NbTiN, a material first developed in the 1960s [8], and more recently used in rf cavities [9], is a promising candidate to fill this need.

In recent years, NbTiN tuning circuits with T_c = 14.5 to 15.5 K have been integrated with Nb-based junctions to produce SIS mixers [10]-[12]. Although the F_{gap} of these NbTiN layers has not been experimentally verified, the measured relationship between F_{gap} and T_c in NbN ($F_{gap} = 3.52\text{-}4.16 \cdot k_B T_c/h$ [13],[14]) predicts that these tuning circuits will be low-loss up to 1.05-1.35 THz. Indeed, the recent demonstration of NbTiN-based SIS receivers with $T_{N,rec}$ = 205 K at 798 GHz [15] and 315 K at 980 GHz [16] confirm this potential up to 1 THz. However, it remains to be shown that this low-loss performance extends above 1 THz.

In this paper, we present waveguide SIS mixers in which Nb/Al-AlO$_x$/Nb junctions are integrated with NbTiN/SiO$_2$/Al tuning circuits. The performance of these mixers is measured between 0.7 and 1.1 THz, and the resulting heterodyne sensitivity of one device is analyzed to evaluate the loss in the NbTiN ground plane at 970 GHz. Finally, these results are compared with those obtained recently using a quasi-optical mixer with a similar NbTiN/SiO$_2$/Al tuning circuit [16].

II. MIXER DESIGN AND FABRICATION

THz mixers are produced by integrating standard 1-μm Nb SIS junctions ($J_c \sim 7.5$ kA/cm^2) with a 300-nm NbTiN ground plane, a 250-nm SiO$_2$ dielectric layer, and a 400-nm Al + 100-nm Nb wiring layer (see Fig. 1). The twin-junction tuning circuit seen in Fig. 1 is used to couple radiation from the waveguide probes to the SIS junctions. An 11-μm wide microstrip transmission line connects the two junctions,

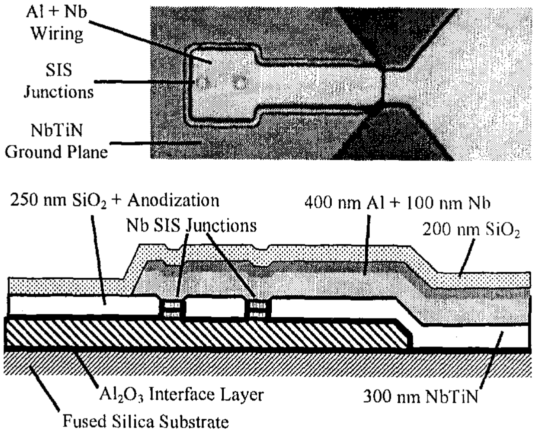

Fig. 1. Microscope image and cross-sectional sketch of the NbTiN/SiO$_2$/Al twin-junction tuning-circuit. The junction separation is 7 μm in this device.

Manuscript received September 17, 2000. This work was supported by the European Space Agency through ESTEC Contract No. 11653/95.

B. D. Jackson, G. de Lange, A. M. Baryshev, W. M. Laauwen, and J.R. Gao are with the Space Research Organization of the Netherlands, P.O. Box 800, 9700 AV Groningen, The Netherlands (telephone: +31-50-363 4051, e-mail: B.D.Jackson@sron.rug.nl).

N. N. Iosad and T. M. Klapwijk are with the Department of Applied Physics (DIMES), Delft University of Technology, Lorentzweg 1, 2628 CJ Delft, The Netherlands.

[1] $T_{N,mix}$ is the effective DSB input noise of the complete mixer unit, from the input of the beam-forming element (waveguide horn or quasi-optical lens) to the IF connector. It includes contributions from the waveguide/lens, antenna, tuning circuit, RF choke, SIS junction, and IF output connection.

which are separated by 4-7 µm. The junctions are connected to the waveguide probes by a 7-µm wide and 18-26 µm long impedance transformer. The waveguide probes and the rf choke structures (not shown) are designed for a 1 THz mixer block with a 120 µm × 240 µm waveguide and a 90 µm × 90 µm substrate channel. Table I summarizes the tuning circuit geometries of the four devices for which results are presented in this paper.

TABLE I
TUNING CIRCUIT GEOMETRIES FOR THE FOUR DEVICES PRESENTED HERE

Device	Tuning Section	Transformer	Junction Area
c07	5.5 x 11	20 x 7	0.58
c13	7 x 11	23 x 7	0.58
c37	5.5 x 11	20 x 7	0.67
c71	4 x 11	18 x 7	0.64

Tuning section and transformer dimensions (length x width) are given in µm. Junction areas are given in µm^2.

The mixers are fabricated on 200-µm thick fused quartz substrates using a process similar to that developed previously for quasi-optical mixers incorporating NbTiN/SiO$_2$/Al tuning circuits [16]. The NbTiN ground plane is deposited using a process that was previously shown [17] to produce films with $T_c = 14.4$ K and $\sigma_{16K} = 0.9\times10^6\ \Omega^{-1}\mathrm{m}^{-1}$, while the sputtered Al has $\sigma_{4K} \approx 2\times10^8\ \Omega^{-1}\mathrm{m}^{-1}$, and is expected to be in the anomalous limit [18]. The only major deviation from the previously described process is that the Al wiring is covered with Nb to reduce the series resistance of the upper wiring layer portion of the rf choke.

III. DC CURRENT-VOLTAGE CHARACTERISTICS

The dc current-voltage (I-V) characteristics of one device (c37) at 4.6 and 2.8 K are seen in Fig. 2. In general, I-V measurements of these devices at 4.6 K yield $V_{gap} = 2.7$-2.82 mV, $R_n{\cdot}A \approx 28\ \Omega{\cdot}\mu\mathrm{m}^2$, $R_n = 20$-$24\ \Omega$ (thus, $A = 0.58$-$0.7\ \mu\mathrm{m}^2$ per junction), and $R_{2.0}/R_n = 10$-17 ($R_{2.0}$ is the resistance of the junction at 2.0 mV, so $R_{2.0}/R_n$ is a measure of the quality of the tunnel junction). An improvement in junction quality is obtained upon cooling to 2.8 K — $V_{gap} = 2.84$-2.90 mV and $R_{2.0}/R_n = 13$-40.

One point of note is that the severe dc heating of the junction electrodes observed in devices incorporating a NbTiN/SiO$_2$/NbTiN [12] tuning circuit is minimal in these devices, as is indicated by the well-behaved I-V curve in Fig. 2. This heating effect has since been attributed to the presence of a heat-flow barrier at the Nb/NbTiN interfaces due to the large superconducting energy gap in NbTiN relative to that in Nb [19]. Thus, replacing one NbTiN layer with Al removes this barrier, allowing heat to escape into the Al wiring.

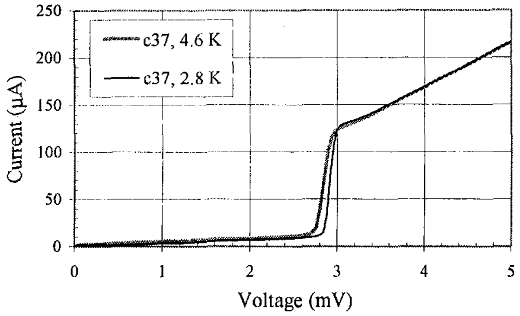

Fig. 2. Current-voltage characteristics of device c37 at 4.6 and 2.8 K.

IV. RF MEASUREMENT SETUP

RF measurements are performed in both tunable and fixed-tuned 1-THz waveguide mixer blocks. The tunable mixer block [5] incorporates a sliding backshort tuner, while the fixed-tuned mixer block has a 60-µm deep stamped backshort cavity. Both mixer blocks have a 120 µm x 240 µm waveguide, a 90 µm x 90 µm substrate channel, and a diagonal horn with an 11° cone angle. Radiation is coupled into the mixer 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 response of each mixer is measured using a Michelson interferometer that is evacuated to eliminate water vapor absorption lines. Heterodyne receiver measurements are performed with 295- and 77-K blackbody loads, backward-wave local oscillators operating from 830 to 1100 GHz, and Mylar beamsplitters of 6- and 14-µm thickness. The IF output power from the mixer is coupled to a 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.

The DSB receiver noise temperature, $T_{N,rec}$, and the effective DSB input noise temperature of the mixer unit, $T_{N,mix}$, are calculated from a Y-factor measurement using the Callen-Welton formulation [20] for the effective temperatures of the blackbody signal loads and the receiver optics. Using an unpumped mixer as a noise source, the noise and gain of the IF system are determined to be 4-5 K and 68 dB in an 85 MHz band centered at 1.46 GHz.

V. RF MEASUREMENT RESULTS

The fixed-tuned direct-detection responses of four devices measured at 4.6 K are shown in Fig. 3. Devices c07, c13, and

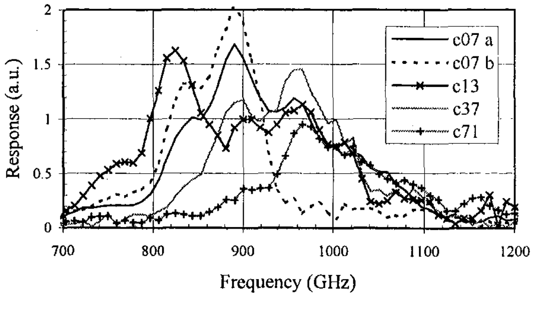

Fig. 3. The direct-detection response of the mixers at 4.6 K. c07, c13, and c71 are measured in the tunable mixer (the backshort depth is 60 µm for c07a, c13, and c71, and 120 µm for c07b). Device c37 is measured in the fixed-tuned mixer.

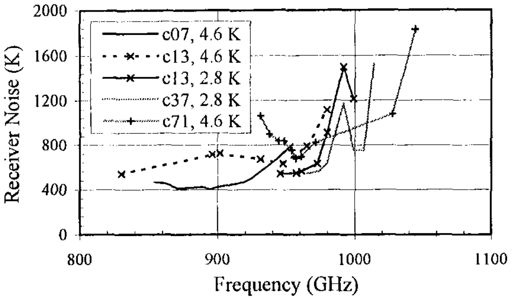

Fig. 4. Heterodyne receiver noise temperatures measured at 4.6 K (c07, c13, and c71) and 2.8 K (c13 and c37). Devices c13, c37, and c71 are measured using a 14-um beamsplitter, while c07 is measured using a 6-um beamsplitter. The dip seen in the sensitivity of c13 and c37 at ~ 990 GHz is due to a water-vapor absorption line.

c71 are measured in the tunable mixer block — c13 and c71 are measured with a backshort depth of 60 μm, while c07 is measured with depths of 60 μm (a) and 120 μm (b). Device c37 is measured in the fixed-tuned mixer block.

In general, it is seen that decreasing the junction separation from 7 μm (c13) to 5.5 μm (c07 and c37) and 4 μm (c71) shifts the resonance to higher frequency, as is expected. However, it is also noted that the four devices have similar high-frequency cut-offs (at ~ 1 THz), despite having significantly different low-frequency roll-offs. This may be attributed to losses in the NbTiN ground plane above 1 THz.

The receiver noise temperatures of the four devices measured at 4.6 and 2.8 K are shown in Fig. 4 (for c07, c13, and c71, the backshort position is optimized for each frequency). 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). The lowest $T_{N,rec}$ near 1 THz is measured at 2.8 K with device c37 and a 14 μm beamsplitter ($T_{N,rec}$ = 565 K and G_{rec} = -12.9 dB at 970 GHz). Similar sensitivities (within 10 %) near 1 THz are obtained with c13 and c71. The 20 % improvement seen in the response of c13 upon cooling from 4.6 to 2.8 K is typical for these devices. Furthermore, the general drop in receiver sensitivities above 1 THz agrees with the observed drop in their direct-detection sensitivities at this frequency.

VI. ESTIMATED LOSSES IN THE NBTIN GROUND PLANE

Focusing on the device with the highest sensitivity near 1 THz (c37 at 2.8 K and 970 GHz), the measured receiver gain is analyzed to estimate the losses in the NbTiN ground plane. In principle, the twin-junction tuning circuit should be modeled using two coupled junctions with different embedding admittances and pumping levels [21]. However, for simplicity, the two junctions are approximated by one model junction with an area equal to $2 \cdot 0.67\ \mu m^2 = 1.34\ \mu m^2$ ($R_n = 21\ \Omega$). This allows us to use the rf-voltage-match method [22], together with measured I-V characteristics, to estimate the embedding admittance for the model junction ($0.12 + 0.04i\ \Omega^{-1}$ at 970 GHz). This embedding admittance is then used in the 3-port Tucker theory [23] to calculate the DSB mixer conversion gain of the model junction. Finally, the loss in the tuning circuit is estimated by subtracting the calculated DSB conversion gain (-7.2 dB) and the estimated optical losses (2.5 dB in the beamsplitter, dewar window, heat filter, and lens) from the measured receiver gain (-12.9 dB). In this manner, the tuning circuit loss is estimated to be ~ 3.2 dB at 970 GHz.

Independent of this estimate, a calculation of the coupling of radiation from the waveguide to the SIS junctions predicts a 2.5- to 3-dB loss in the Al wiring layer (assuming NbTiN to be a loss-less superconductor [3]). If this estimate is subtracted from the 3.2 dB loss in the tuning circuit, the loss in the NbTiN ground plane is estimated to be < 0.6 dB. The accuracy of this estimate is limited by uncertainties in the embedding admittance, and in the losses in the receiver optics and Al wiring layer. However, it is also assumed that the waveguide, the Al/Nb rf-choke sections, the SiO_2 dielectric layer, and the Nb junction electrodes are each loss-less. Thus, it is concluded that the NbTiN ground plane is, indeed, relatively low-loss up to 970 GHz.

VII. DISCUSSION

In general, the best values of $T_{N,rec}$ reported here are higher than those obtained using a quasi-optical mixer with a similar tuning circuit [16] ($T_{N,rec}$ = 305 K at 970 GHz was reported). However, it is also noted that the receiver optics used in that experiment were considerably more transparent than those used here (G_{opt} = -1.2 dB at 970 GHz, versus -2.5 dB). This makes it difficult to compare the waveguide and quasi-optical mixers on the basis of the measured receiver sensitivities. Fortunately, a comparison of the intrinsic sensitivity of the mixer units ($T_{N,mix}$, G_{mix}) can be obtained by correcting $T_{N,rec}$ and G_{rec} for the noise contributions of the optics ($T_{N,opt}$, G_{opt}) and IF chain ($T_{N,IF}$ = 4 to 5 K). The results of this calculation are summarized in Table II for devices c07 and c37, and the recently demonstrated quasi-optical mixer.

TABLE II

RECEIVER AND MIXER SENSITIVITIES OF DEVICES C07 AND C37, AND A QUASI-OPTICAL MIXER WITH A NBTIN/SIO_2/AL TUNING CIRCUIT [16]

Device	$T_{N,rec}$, G_{rec}	$T_{N,opt}$, G_{opt}	$T_{N,mix}$, G_{mix}
C07 (895 GHz, 4.6 K)	425, -11.4	61, -1.5	207, -9.9
C37 (970 GHz, 2.8 K)	563, -12.9	146, -2.5	182, -10.4
QO mixer (900 GHz, 4.6 K)	340, -9.7	31, -1.1	205, -8.6
QO mixer (970 GHz, 2.8 K)	305, -10.3	35, -1.2	166, -9.2

$T_{N,rec}$, $T_{N,mix}$, and $T_{N,opt}$ are given in K. G_{rec}, G_{opt}, and G_{mix} are in dB.

Comparing the values of $T_{N,mix}$ in Table II, it is seen that the two most sensitive waveguide mixers (c07 and c37) have sensitivities that are comparable to that of the quasi-optical mixer. However, it also noted that the quasi-optical mixer is sensitive over a much wider frequency band (820 to 1020 GHz) than the mixers presented here. Thus, although the peak sensitivities of the two types of mixer are similar, further work is needed to increase the rf bandwidth of the waveguide mixers (rf bandwidths of ~ 160 GHz are desired).

Furthermore, although the estimated 3-dB loss in the $NbTiN/SiO_2/Al$ tuning circuits is much lower than in an all-Al tuning circuit (5 to 9 dB in [6],[7]), it continues to limit the mixer performance. Thus, it should be possible to produce mixers with improved sensitivities by incorporating recent improvements in the production of SIS junctions with very-high J_c (up to 50 kA/cm^2) [24] (which will reduce the loss in the Al wiring layer).

Finally, further work is also needed to improve the sensitivity of both the waveguide and the quasi-optical mixers above 1 THz. In particular, the observed cut-off in sensitivity at ~ 1 THz is a concern, as it is at least 50 GHz lower than the predicted F_{gap} of a NbTiN film with T_c = 14.4 K (1.05 to 1.25 THz is expected). The source of this discrepancy needs to be confirmed. However, one likely explanation is the non-homogeneity in the electrical properties of NbTiN films deposited at room temperature [25]. (Grains with particularly low values of T_c may introduce rf losses below the F_{gap} of the bulk film, but may not be seen in a resistive measurement of T_c.) Based upon this evidence, one means of increasing the cut-off frequency is clear — the use of higher-quality NbTiN layers (with higher T_c and improved homogeneity), such as those deposited on MgO substrates [10],[25].

VIII. CONCLUSIONS

Waveguide SIS mixers incorporating Nb tunnel junctions and NbTiN/SiO$_2$/Al tuning circuits are shown to yield receiver noise temperatures as low as 425 and 565 K at 895 and 970 GHz, respectively. Following an analysis of the noise and gain of one mixer, it is concluded that the loss in the NbTiN ground plane is relatively low (< 0.6 dB) at 970 GHz. Furthermore, although an observed drop in receiver sensitivity above 1 THz is attributed to increasing losses in the NbTiN ground plane, it is noted that it should be possible to increase this cut-off frequency by incorporating higher-quality NbTiN films. Finally, it is shown that the results presented here are in good agreement with those reported previously for a quasi-optical mixer with a similar NbTiN/SiO$_2$/Al tuning circuit [16].

ACKNOWLEDGMENT

The authors would like to thank M. Eggens, L. de Jong, D. Nguyen, C. Pieters, and H. Schaeffer for their technical assistance and P. de Korte, H. van de Stadt, N. Whyborn, B. Bumble, R. LeDuc, J. Stern, and J. Zmuidzinas for helpful discussions.

REFERENCES

[1] J. W. Kooi et al., "230 and 492 GHz low noise SIS waveguide receivers employing tuned Nb/AlO$_x$/Nb tunnel junctions," *Int. J. IR and MM Waves*, vol. 16, pp. 2049-2068, Dec. 1995.

[2] A. Karpov, J. Blondel, M. Voss, and K. H. Gundlach, "A three photon noise SIS heterodyne receiver at submillimeter wavelength," *IEEE Trans. Appl. Supercon.*, vol. 9, pp. 4456-4459, June 1999.

[3] D. C. Mattis and J. Bardeen, "Theory of the anomalous skin effect in normal and superconducting metals," *Phys. Rev.*, vol. 111, pp. 412-417, July 1958.

[4] G. de Lange et al., "Superconducting resonator circuits at frequencies above the gap frequency," *J. Appl. Phys.*, vol. 77, pp. 1795-1804, Feb. 1995.

[5] H. van de Stadt et al., "A 1 THz Nb SIS heterodyne mixer with normal metal tuning structure," in *Proc. of the 6th Int. Symp. on Space THz Technol.*, CIT, Pasadena, CA, March 21-23, pp. 66-77, 1995.

[6] 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.*, vol. 68, pp. 1714-1716, Mar. 1996.

[7] P. Dieleman, T. M. Klapwijk, J. R. Gao, and H. van de Stadt, "Analysis of Nb superconductor-insulator-superconductor tunnel junctions with Al striplines for THz radiation detection," *IEEE Trans. Appl. Supercon.*, vol. 7, pp. 2566-2569, June 1997.

[8] J. R. Gavaler, J. K. Hulm, M. A. Janocko, and C. K. Jones, "Preparation and superconducting properties of thin films of transition metal interstitial compounds," *J. Vac. Sci. Technol.*, vol. 6, pp. 177-180, 1968.

[9] R. di Leo, A. Nigro, G. Nobile, and R. Vaglio, "Niobium-titanium nitride thin films for superconducting rf accelerator cavities," *J. Low Temp. Phys.*, vol. 78, pp. 41-50, Nov. 1990.

[10] 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," in *Proc. of the 9th Int. Symp. on Space THz Technol.*, CIT, Pasadena, CA, pp. 305-313, March 17-19, 1998.

[11] J. W. Kooi et al., "Low-loss NbTiN films for THz SIS mixer tuning circuits," *Int. J. IR and MM Waves*, vol. 19, pp. 373-383, Mar. 1998.

[12] B. D. Jackson et al., "DC and terahertz response in Nb SIS mixers with NbTiN striplines," in *Proc. of the 10th Int. Symp. on Space THz Technol.*, U. of Virginia, Charlottesville, VA, pp. 144-156, March 16-18, 1999.

[13] N. Yoshikawa, H. Su, K. Fukushima, and M. Sugahara, "Study of electron conduction properties of NbN thin films using NbN/MgO/NbN double junctions," in *Proc. of the 5th Int. Superconductive Elec. Conf.*, Nagoya, Japan, pp. 450-452, September 18-21, 1995.

[14] Z. Wang, A. Kawakami, Y. Uzawa, and B. Komiyama, "Superconducting properties and crystal structures of single-crystal niobium nitride thin films deposited at ambient substrate temperature," *J. Appl. Phys.*, vol. 79, pp. 7837-7842, May 1996.

[15] J. Kawamura et al., "Low-noise submillimeter-wave NbTiN superconducting tunnel junction mixers," *Appl. Phys. Lett.*, vol. 75, pp. 4013-4015, Dec. 1999.

[16] B. D. Jackson et al., "Low-noise 1 THz superconductor-insulator-superconductor mixer incorporating a NbTiN/SiO$_2$/Al tuning circuit," *Appl. Phys. Lett.*, submitted for publication.

[17] N. N. Iosad et al., "Source optimization for magnetron sputter-deposition of NbTiN tuning elements for SIS THz detectors," *Supercon. Sci. Technol.*, vol. 12, pp. 736-740, Nov. 1999.

[18] R. L. Kautz, "Miniaturization of normal-state and superconducting striplines," *J. Res. Natl. Bur. Std.*, vol. 84, pp. 247-259, May-June 1979.

[19] 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.*, vol. 76, pp. 780-782, Feb. 2000.

[20] H. B. Callen and T. A. Welton, "Irreversibility and generalized noise," *Phys. Rev.*, vol. 83, pp. 34-40, July 1951.

[21] J. Zmuidzinas, H. G. LeDuc, J. A. Stern, and S. R. Cypher, "Two-junction tuning circuits for submillimeter SIS mixers," *IEEE Trans. Microwave Theory Tech.*, vol. 42, pp. 698-706, Apr. 1994.

[22] A. Skalare, "Determining embedding circuit parameters from DC measurements on quasiparticle mixers," *Int. J. IR and MM Waves*, vol. 10, pp. 1339-1354, Nov. 1989.

[23] J. R. Tucker and M. J. Feldman, "Quantum detection at millimeter wavelengths," *Rev. Mod. Phys.*, vol. 57, pp. 1055-1113, Oct. 1985.

[24] J. Kawamura et al., "Very high-current-density Nb/AlN/Nb tunnel junctions for low-noise submillimeter mixers," *Appl. Phys. Lett.*, vol. 76, pp. 2119-2121, Apr. 2000.

[25] N. N. Iosad et al., "Superconducting transition metal nitride films for THz SIS mixers," *IEEE Trans. Appl. Supercon.*, submitted for publication.