Performance and modeling of 700 GHz SIS finline mixers

Paul K. Grimes, Ghassan Yassin, Stafford Withington and Karl Jacobs.

***Abstract*—SIS mixers using finline waveguide to microstrip transitions show a number of advantageous features, particularly in providing a broadband, fixed impedance feed to the SIS mixer tuning circuit. The large chip area and insensitivity to mixer block machining tolerances simplifies the assembly of the mixer, as well as allowing more advanced mixer designs to be fabricated on a single chip. Finline SIS mixers have shown good performance in the 230 and 350 GHz bands[1][2], and we have also previously reported results from two finline SIS mixers in the 600-720 GHz band[3][4], obtaining best receiver noise temperatures of ~250 K.**

In this paper we present results from several finline mixers in the 600-720 GHz band, using both variants of our original 3-stage Chebyshev filter tuned single junction mixers and new Belitsky tuned mixers. These dual junction tuned mixers show significantly better performance than our previously reported results, with receiver noise temperatures below 200 K.

We present detailed SuperMix simulations of the receiver performance and compare these with measured results. We find good agreement between simulations and measured performance can be achieved by introducing a small amount of attenuation in the RF circuit of the mixer. We also present simulations of the IF bandwidth of finline mixers, and suggest a method by which this can be greatly improved.

I. Introduction

Superconductor-Insulator-Superconductor (SIS) mixers are commonly used as coherent detectors in millimeter and sub-millimeter wave astronomy, and are the basis of the most sensitive receivers at frequencies up to a 1 THz. Modern niobium based SIS mixers achieve sensitivities comparable to the quantum limit at frequencies up to the superconducting energy gap of niobium (680 GHz). However, above the gap losses in the niobium transmission lines become significant, while losses in other components of the receiver also increase, and so careful analysis and design of the complete receiver system is required to achieve the best possible performance.

In this paper we report results from seven finline SIS mixers operating in the 600-720 GHz band, i.e. across the superconducting energy gap of niobium. While finline mixers have a number of important advantages, the long length of niobium superconducting transmission line that makes up the finline taper means that losses may be very large at frequencies above the superconducting gap. We have therefore used experimental techniques and numerical simulations to separate the various contributions to the receiver performance, with the aim of determining the performance of the finline tapers across the superconducting energy gap.

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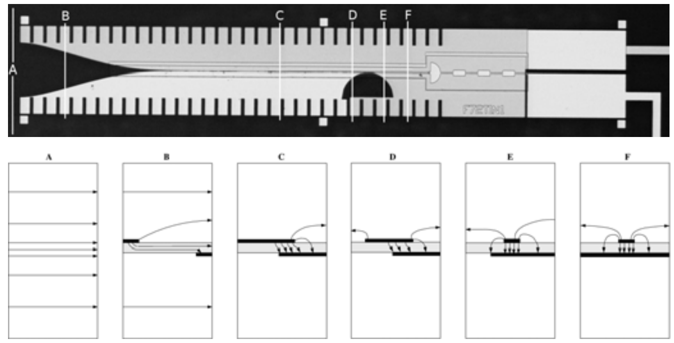

Fig. 1. (Top) A 700 GHz finline mixer chip. The finline taper runs from the left to center of the chip, and the mixer tuning circuit, RF block and bond pads are on the right (Bottom) Cross-sections through the finline taper, showing the metallization and the E-field lines. The finline taper gradually transforms the waveguide mode at A through unilateral finline (B) to antipodal finline (C), before transitioning from antipodal finline to microstrip (D-F).

Finline tapers have been successfully used on many mm-wave superconducting detectors, including our previously reported 230 and 350 GHz SIS mixers and a 700 GHz balanced mixer. We have also recently designed finline tapers for the 100 GHz TES detectors for Clover[5], and a 230 GHz cold electron bolometer. We have demonstrated that these tapers provide a broadband mixer feed that does not require a complex mixer block or any mechanical tuning and provide a large substrate area that is suitable for high levels of integration. Once the RF signal has passed to the microstrip output of the finline taper, the waveguide surrounding the chip can be removed, allowing great flexibility in processing the RF signal and in extracting IF signals from the chip.

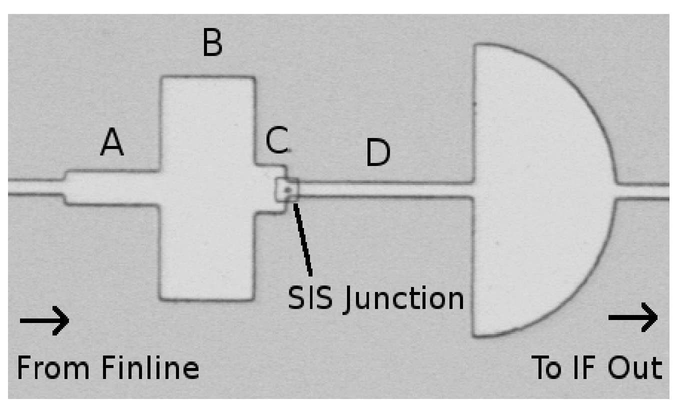

Fig. 2. The 3-stage Chebyshev tuned mixer and radial RF-choke design. Typical dimensions are: **A** 7 x 26 µm, **B** 46 x 24 µm, **C** 10 x 6.5 µm and **D** 3 x 39 µm.

II. THE 700 GHZ FINLINE MIXER DESIGN

A. Mixer chip

The mixer chip (Fig. 1) is deposited in five steps, using four UV lithography masks. First a Nb-AlOx-Nb trilayer is deposited (200 nm, 10 nm, 100 nm). The junction is then defined by reactive ion etching, and the first SiO dielectric layer (200 nm) is evaporated using the same photoresist mask. A second layer of SiO is deposited to thicken the dielectric layer to 425 nm. Finally the 400 nm Nb wiring layer (with a 25 nm Au protection layer on top) is sputtered, forming the upper fin, mixer wiring and bond pads.

The mixer is deposited on a 225 µm fused quartz (infrasil) wafer, which is diced and then lapped to 45-60 µm thickness on a dicing saw after fabrication. A triangular taper is diced onto the front of the mixer chip to prevent reflections from the front of the mixer chip.

The finline taper consists of two niobium fins deposited on the quartz mixer chip, that gradually extend from the walls of the E-plane of the waveguide until they overlap at the centre of the waveguide. The fins are separated in the overlap region by a 0.425 µm layer of evaporated SiO. Once the fin overlap is large enough that fringing effects can be ignored, the top fin is tapered away from the wall to form the wiring layer of the output microstrip and mixer circuit, before the lower fin (the lower layer of the trilayer) is extended across the waveguide to form the ground plane of the microstrip (Fig. 1).

The finline taper is designed using a mixture of transverse resonance and spectral domain analysis as the inputs to an optimum taper method. Details of the electromagnetic design have already been reported[6].

The 20 Ω microstrip feeds the mixer tuning circuit, containing the SIS junction(s). A second microstrip carries IF signals from the output of the mixer tuning circuit to bond pads at the end of the chip. DC bias signals are also applied to the SIS junction via these bond pads and microstrip.

Results from mixers using two different types of tuning circuits are presented in this paper. The first design tested consists of a 3-section microstrip Chebyshev transformer (Fig. 2) that transforms the 20 Ω input microstrip impedance to the 20 Ω plus 65 fF capacitance of the SIS junction. This circuit was optimized using Sonnet em suite to maximize the RF coupling to the SIS junction.

The second circuit (Fig. 3) uses a two junction (or

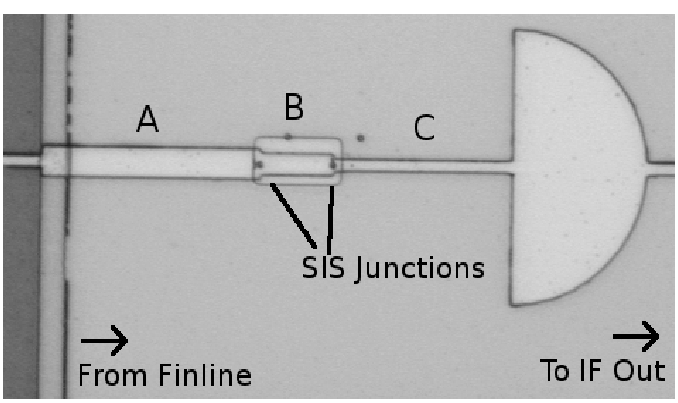

Fig. 3. The dual junction tuned mixer and radial RF-choke design. Typical dimensions are: **A** 7 x 48.5 µm, **B** 5 x 15.5 µm and **C** 3 x 39 µm.

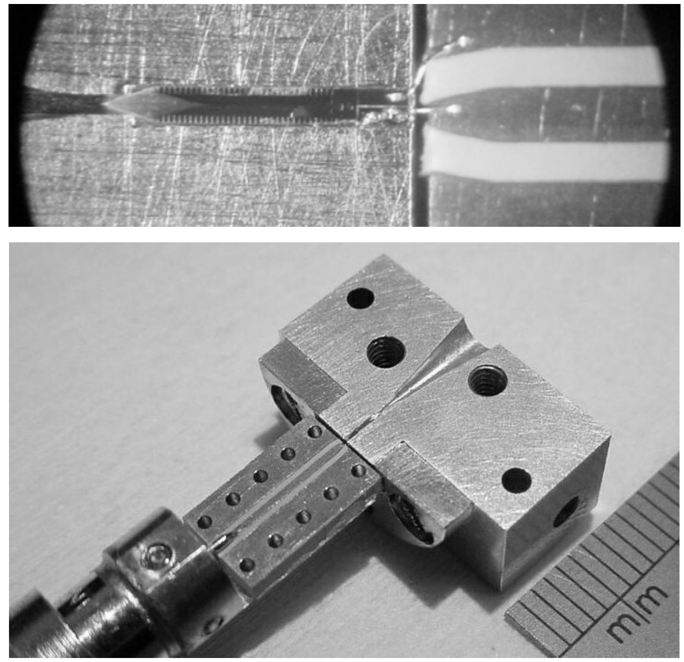

Fig. 4. (Top) The mixer chip mounted in the split mixer block and bonded to the CPW IF board. (Bottom) One half of the split mixer block, showing the SMA connector, IF board, mixer chip and Pickett-Potter horn.

"Belitsky"[7]) tuning circuit, consisting of two SIS junctions separated by a length of microstrip, and with a quarter-wave section of microstrip to match the 20 Ω input microstrip to the 10 Ω normal resistance of the two parallel SIS junctions. The capacitance of one junction, transformed by the microstrip section, cancels out the capacitance of the second junction[8]. This circuit was optimized using SuperMix[9] to give the maximum conversion gain across a broad RF bandwidth. In both circuits the IF signal from the junction is readout via a radial stub RF choke to prevent RF signal leaking into the IF circuit.

B. Mixer block

The split mixer block is directly machined in aluminum in two halves, joined along the E-plane of the 160 µm by 320 µm waveguide. The mixer chip is superglued into a pair of 60 µm

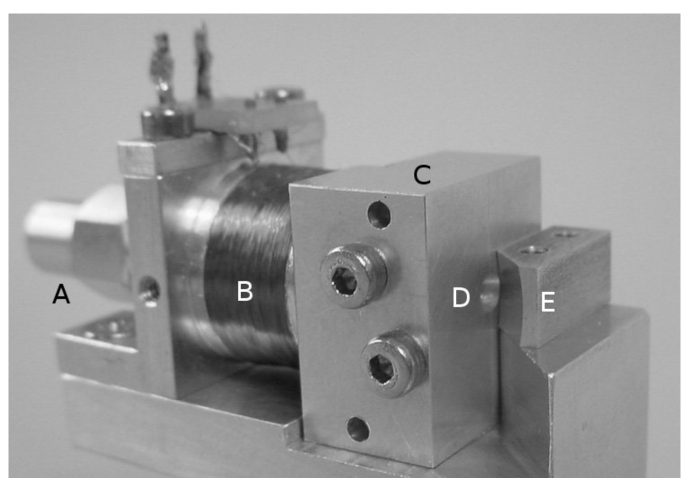

Fig. 5. The assembled mixer block and support jig. Visible components include: **A** SMA connector, **B** electromagnet, **C** split mixer block, **D** horn aperture and **E** offset parabolic reflector.

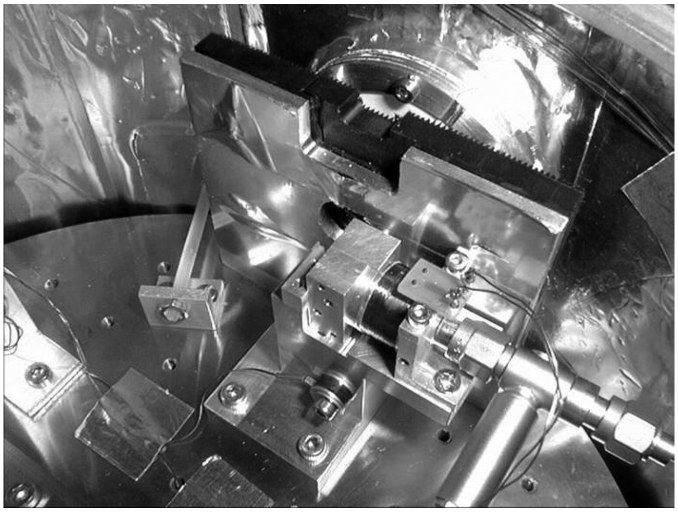

Fig. 6. The mixer assembled into the He4 cryostat. The horn-reflector aperture is to the top left of the mixer block, point through the circular aperture in the TK RAM shield. The Zitex IR filter can be seen over the top of the shield.

wide by 60 µm deep grooves machined into the waveguide walls in one half-block (Fig. 4).

The mixer is fed by a Pickett-Potter Horn Reflector (PPHR) antenna[3] directly machined in two halves into the mixer block, with the offset parabolic reflector (used to correct the spherical phase cap) mounted onto the jig holding the mixer block (Fig. 5). This feed is relatively simple to machine, and provides a good radiation pattern across the mixer band.

The mixer chip is bonded to a short section of co-planar waveguide on RT/Duroid 6010LM that carries the IF and bias signals to an SMA connector mounted on the back of the mixer block (Fig. 4). A superconducting electromagnet mounted coaxially with the IF board and mixer chip is used to suppress the Josephson current in the SIS junction (Fig. 5).

C. *Test receiver*

Experimental investigation of the mixer performance was carried out by mounting the mixer block in an IR labs He4 wet cryostat, looking out through a thermal filter consisting of 4 thin layers of Zitex and through either a resonant 610 um HDPE vacuum window or a 2.5 mm thick HDPE window with corrugated antireflection grooves machined into the surface. A small area of Thomas Keating RAM tiles with an aperture around the beam are positioned between the mixer block and the thermal filters to help prevent standing waves (Fig. 6). For most of the measured data in this paper, the cryostat was cooled to below 2.4 K by pumping on the helium bath.

The IF and bias signals are separated in a Radiall 0-12 GHz bias tee. The IF signal is then amplified by a Berkshire 4-6 GHz cryogenic LNA with a nominal noise temperature less than 4 K, before being passed out of the cryostat to the warm IF electronics, consisting of a 4.2-5.8 GHz bandpass filter, two amplifiers and a diode power detector.

LO power was provided by a RPG Gunn diode, doubler, tripler chain providing up to 330 µW across a 600-720 GHz band. The LO beam is focused by an offset parabolic mirror and then coupled to the mixer via a 8.5 µm or 18 µm Mylar beam splitter.

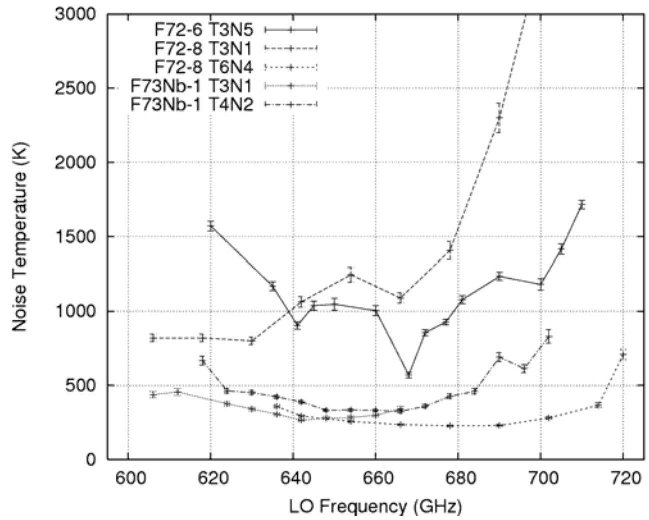

Fig. 7. Measured noise performance for five 3-stage Chebyshev transformer tuned mixers. All of these measurements were carried out at a physical temperature of 2.5 K.

III. Measured Performance

Five 3-stage Chebyshev tuned devices (from 3 fabrication batches) and two dual junction tuned devices (from the final fabrication batch) were selected for testing on the basis of their measured IV curves. Devices with suitable normal resistances, low subgap leakages and Fiske resonances close to the expected values were chosen for full RF testing. Noise and gain performance of these devices is given in Figs. 7-10.

Noise performance was determined using the Y-factor method with 77 K and 297 K Eccosorb loads, while conversion gain was determined by comparing the IF output power for the two loads, after calibrating the gain of the IF chain using the unpumped SIS junction biased above the gap as a noise source. No corrections have been applied to receiver noise temperatures, and the Rayleigh-Jeans

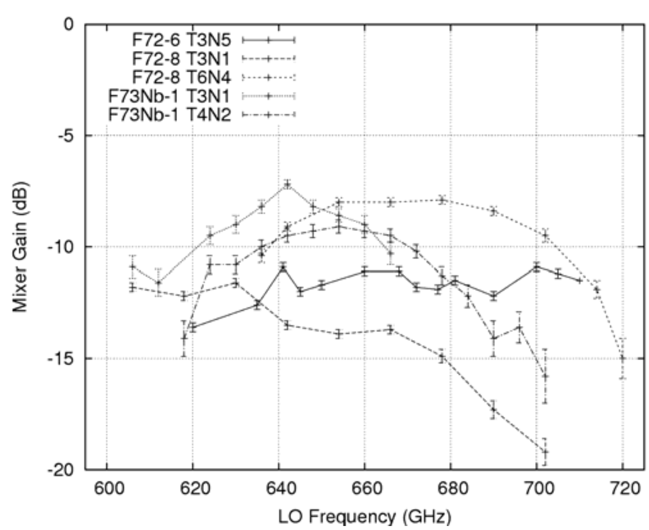

Fig. 8. Measured conversion gain for the five 3-stage Chebyshev transformer tuned mixers of Fig. 7. The IF system gain is calibrated, and the conversion gain referred to front of the IF amplifier by using the unpumped SIS junction, biased well above the gap, as a noise source.

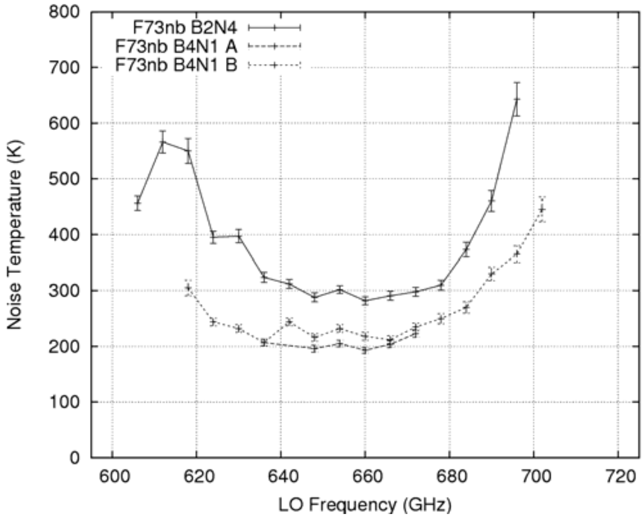

Fig. 9. Measured noise performance for two dual junction tuned mixers. Device F73nb-1 B4N1 was measured twice, with significantly better performance recorded over a reduced frequency range on the first attempt.

approximation is used in determining load powers, leading a to slight overestimation of the receiver noise.

Of the five Chebyshev tuned devices, the first two devices tested (F72-6 T3N5 and F72-8 T3N1) were deliberately chosen because they were tuned above 700 GHz and below 620 GHz respectively, in order to give reasonable direct detection sensitivity for measuring the Pickett-Potter horn reflector antenna radiation pattern at the edges of the band. The heterodyne performance of these devices was measured using an older cryogenic IF LNA, with a noise temperature of ~10 K. As expected, the performance of these devices is compromised by both the poor tuning and noisier IF chain. These devices were tested using the corrugated Dewar window. In subsequent tests, better performance was obtained with the thin resonant Dewar window, and this window was used for all other results.

The other three devices tested were all well tuned, and were

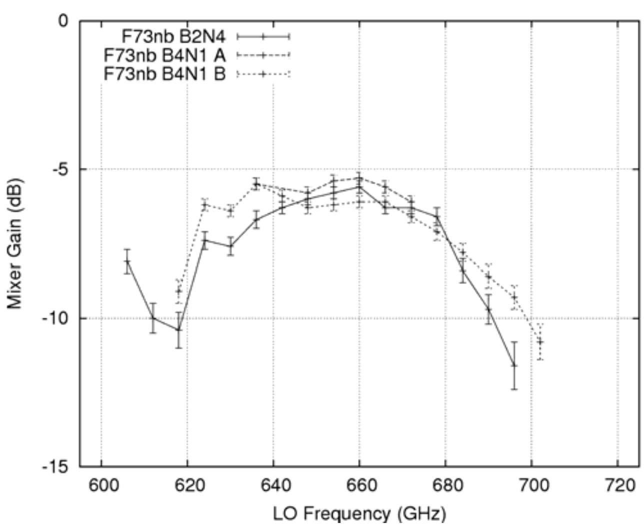

Fig. 10. Measured conversion gain for the two dual junction tuned mixers of Fig. 9. Again, device F73nb-1 B4N1 showed significantly better performance over a narrow frequency range in the first experiment.

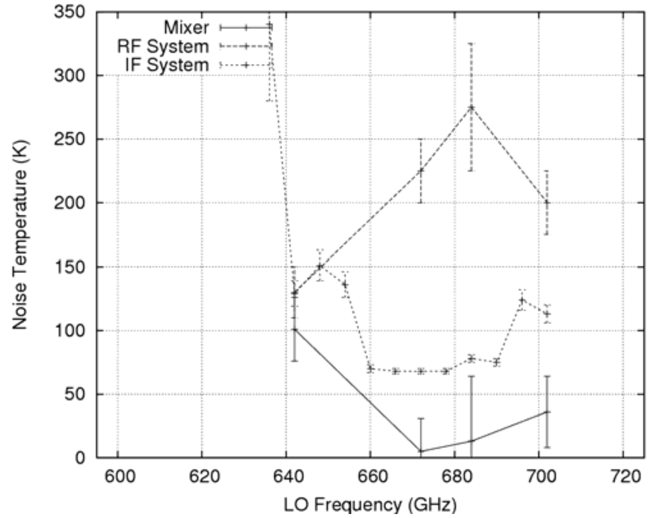

Fig. 11. Measured contributions from receiver components to the total receiver noise for device F72-8 T6N4. The IF noise is estimated from the measured conversion gain and IF amplifier input noise temperature (both measured directly for the bare amplifier, and as part of the receiver system, using the method of [10]), while the RF side noise contribution is estimated at selected frequencies using the intersecting lines method[11]. The remaining system noise is assigned to the mixer itself.

tested using the IF amplifier described in II.C. All of these devices showed conversion gains between -8 and -10 dB and noise temperatures below 400 K across the centre of the LO band, with best values of -8 dB and 250 K for F72-8 T6N4 between 666 and 690 GHz. The performance below 640 GHz for all devices is limited by the available LO power, while at the top edge of the band the performance is limited by both the available LO power and by the above gap losses in the finline and mixer tuning circuit.

For the best device (F72-8 T6N4), the intersecting lines method was used at selected frequencies to estimate the noise contribution of from the RF circuits and optics, while the measured conversion gain was used to estimate the IF system contribution to the noise. The results of this analysis are shown in Fig. 11 and suggest that the noise of the receiver is dominated by losses in the RF circuit and/or optics.

The two dual junction devices tested show better conversion gain and noise performance than the single junction devices, with best values of -5.3 dB and 196 K for device F73nb-1 B4N1 at 660 GHz.

The direct coupling and heterodyne bandwidth of these two devices is significantly wider than for the single junction devices, making it much easier to couple LO power. However both devices are still under-pumped at frequencies below 624 GHz. The performance of device F73nb-1 B4N1 was significantly better during a preliminary test at the centre of the band than when the full LO band was measured during a second experiment, probably due to a change in the test receiver optics between the two experiments.

IV. Simulations of Receiver Performance

Caltech's SuperMix simulation library[9] was used to model the performance of the complete receiver. The receiver

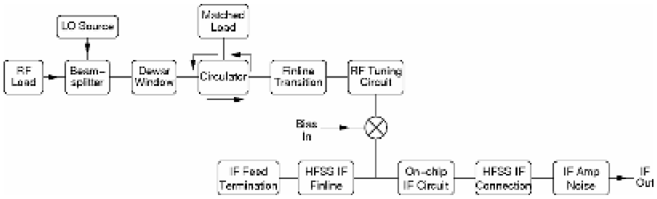

Fig. 12. SuperMix circuits used to simulate the performance of the complete 700 GHz finline test receiver. The top circuit consists of RF frequency components, while the lower circuit consists of the IF components.

is modeled using the RF and IF circuits shown in Fig. 12. The RF circuit consists of the hot/cold load, LO source (with 300 K sideband noise temperature), beamsplitter, Dewar window, finline transition and the mixer tuning circuit. The finline transition is modeled as a circulator with matched load to provide input matching and a length of superconducting microstrip to model the above gap losses. The IF circuit includes the IF representation of the mixer chip circuits, finline taper and bondwire connection to the IF board CPW line, as well as a constant noise temperature due to the IF amplifier.

A. *Component modeling*

Several new classes were created within SuperMix to allow the whole receiver system to be modeled. The main two components required were 2 and 3 port models of a dielectric slab placed within the free space beam. These components were used to represent the HDPE resonant window and the Mylar beamsplitter, and can represent a dielectric slab at an any angle to the beam in either parallel or perpendicular polarization. The scattering parameter calculations for these components were derived from the reflection and transmission properties given by Goldsmith[12]. A basic check of the model was carried out by calculating the transmission through the Dewar vacuum window and comparing this with FTS measurements of the window, which showed good agreement.

The effect of the finline taper is included in the simulations using two methods. For RF signals only the above gap losses of the finline are modeled by including a length of superconducting microstrip, chosen to match the decrease in conversion gain above the gap. For IF signals the finline is modeled using Ansoft's HFSS electromagnetic simulation software. HFSS is also used to model the bondwire connections between the mixer chip and the IF CPW

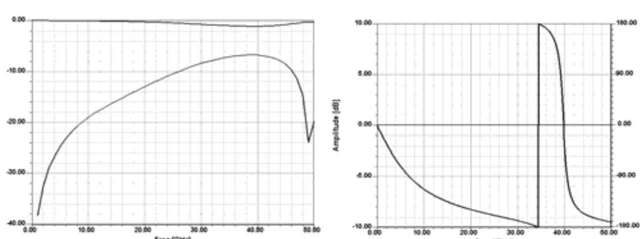

Fig. 13. (Left) Magnitude of HFSS simulated scattering parameters for the bondwire connection between the mixer chip and the IF board for IF frequencies up to 50 GHz. (Right) Magnitude and phase of the IF signal reflected from the finline taper as a function of IF frequency. The finline appears as an open circuit at 0 and 40 GHz, and as a short circuit at 34 GHz.

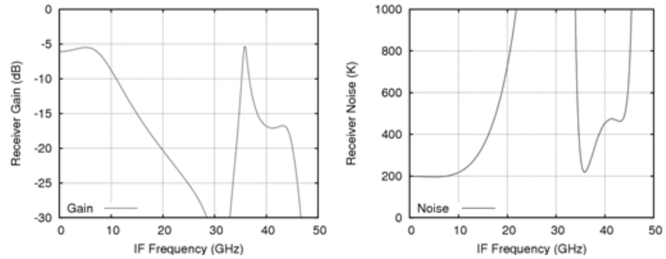

Fig. 14. SuperMix simulated performance of device F73nb-1 B4N1 as a function of IF frequency. The variation in performance is dominated by the effect of the phase of reflections from the finline taper.

connection board. The response of these two IF components are shown Fig. 13.

At IF frequencies, the finline taper is perfectly reflecting (as the IF signals are below the cut-off frequency of the waveguide), the but the point along the finline at which this reflection occurs is strongly frequency dependent, as the cut-off frequency is tapered along the finline. This gives a frequency dependent phase change in the reflection. Simulating the mixer performance as a function of IF frequency (Fig. 14) shows that this property of the finline taper limits the IF bandwidth of the mixer to around ~8-10 GHz, but has little effect below this frequency.

B. *Receiver performance modeling*

A number of parameters are varied in the SuperMix model to fit the simulated mixer performance to the measured performance. These parameters are: LO power (assumed to be that required to give optimum conversion gain), junction capacitance (chosen to give correct shape to the gain at subgap frequencies), and the length and gap voltage of the microstrip representing the finline (chosen to give the correct slope and frequency turn-over point at high frequencies). An additional attenuation at variable temperature is included in the RF circuit (between the Dewar window and the finline) to fit the overall conversion gain and receiver noise temperature.

These parameters were independently fitted to the measured performance of the best devices of each type (F72-8 T6N4, Fig. 15 and F73nb-1 B4N1, Fig. 16.). The performance of these devices can be fitted using similar parameters in both simulations. These parameters are given in Table. 1.

From these results, it appears that there is an additional RF loss of -2.5 to -3.5 dB in the receiver, with an effective temperature of 100-120 K. Obviously this may be made up of several components, at different points in the system, and may not only be in the RF system of the receiver.

TABLE I
FITTED SIMULATION PARAMETERS

Quantity	Fitted Values
Junction capacitance	65-72 fF
LO power	10-12 μW
LO sideband temperature	300 K
Finline equivalent length	600 μm
Finline gap voltage	2.77 mV (670 GHz)
RF Attenuation	-2.5 - -3.5 dB
RF Attenuator Temperature	100-120 K

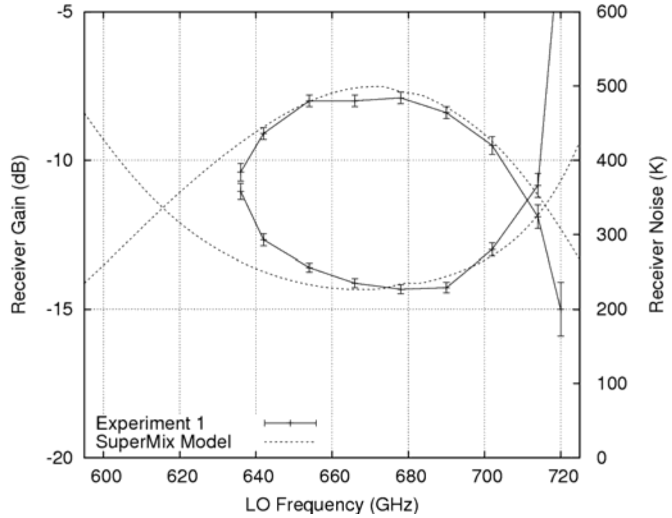

Fig. 15. Comparison of measured data for Chebyshev tuned device F72-8 T6N4 and SuperMix simulated receiver performance.

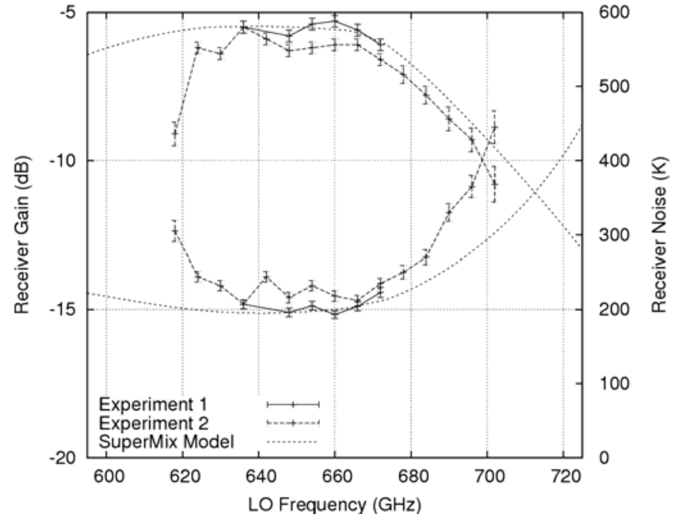

Fig. 16. Comparison of measured data for dual junction tuned device F73nb-1 B4N1 and SuperMix simulated receiver performance.

We suggest several possible sources for this attenuation: losses in the Mylar beamsplitter due to water vapor absorbed in the lab environment; attenuation in the IR filters on the 77 K shield of the Dewar; and losses in the IF board, bias tee and coax used to connect the mixer chip to the IF amplifier.

V. Conclusions and Future Prospects

We have measured several 700 GHz finline mixers using two different tuner designs, and obtained best uncorrected receiver noise temperatures of 250 K and 196 K for each design. The performance of these receivers has been extensively modeled, and good agreement can be obtained between the measured and simulated performance if an extra ~3 dB of attenuation is included in the RF system of the mixer.

We have demonstrated that finline mixers can be operated at frequencies approaching the superconducting gap of niobium. More work will be required to extend operation above the superconducting gap, such as shortening the taper using a more rigorous method of taper design, and/or employing NbTiN films in the taper. Thinner substrates will also substantial improve the performance.

Finally we would like to emphasize that back-to-back finline transitions are ideal for realizing balanced and image separating mixer designs, in which the signal is fed from one finline and the LO from the other. The large substrate area allows the required hybrids to fabricated on-chip, in elegant planar circuits. We have already designed and fabricated a balanced finline mixer based on this concept (Fig. 17)[13] and testing of these devices is currently in progress.

References

[1] G. Yassin, R. Padman, S. Withington, K. Jacobs and S. Wulff, “A broad band antipodal finline mixer for astronomical imaging arrays”, Electron. Lett., vol. 33, pp. 498.

[2] G. Yassin, S. Withington, M. Buffey, K. Jacobs and S. Wulff, “A 350-G Hz SIS antipodal finline mixer”, IEEE Trans. Microwave Theory and Tech., 48, p. 662, 2000.

[3] P. Kittara, P. K. Grimes, G. Yassin, S. Withington, K. Jacobs, and S. Wu lff, “A 700 GHz antipodal finline mixer fed by a Pickett-Potter horn-reflector antenna”, IEEE Trans. Microwave Theory and Tech., 52, p. 2352, 2004.

[4] P. K. Grimes, P. Kittara, G. Yassin, S. Withington and K. Jacobs, “Investigation of the performance of a 700 GHz finline mixer”, Proc. 14th Int. Symp. Space THz Tech., Tucson AZ, 2003.

[5] D. M. Audley *et al*, “Prototype finline-coupled TES bolometers for CLOVER”, Proc 17th Int. Symp. Space THz Tech., Paris, 2006.

[6] C.E. North, G. Yassin and P.K. Grimes, “Rigorous analysis and design of finline tapers for high performance millimetre and submillimetre detectors”, Proc. 17th Int. Symp. Space THz Tech., Paris, 2006.

[7] V.Y. Belitsky and M.A. Tarasov, “SIS junction complete reactance compensation”, IEEE Trans. Magn., 27, pp 2938-2641, 1991.

[8] J. Zmuidzinas, H. G. LeDuc, J.A. Stern and S.R. Cypher, “Two-junction tuning circuits for submillimeter SIS mixers”, IEEE Trans. Microwave Theory and Tech., 42, p. 698-706, 1994.

[9] J. Ward, F. Rice, G. Chattopadhyay and J. Zmuidzinas, “SuperMix: A flexible software library for high-frequency circuit simulation, including SIS mixers and superconducting elements”, Proc. 10th Int. Symp. Space THz Tech., 1999.

[10] D.P. Woody, R.E. Miller and M.J. Wengler, “85-115 GHz receivers for radio astronomy”, IEEE Trans. Microwave Theory and Tech., 33, p. 90-95, 1985.

[11] R. Blundell, R.E. Miller and K.H. Gundlach, “Understanding noise in SIS receivers”, Int. J. Infrared Millimeter Waves, 13, p. 3-14, 1992

[12] P.F. Goldsmith, “Quasioptical systems: Gaussian beam quasioptical propagation and applications”, John Wiley & Sons, Inc., 1997.

[13] P.K. Grimes, G. Yassin, K. Jacobs and S. Withington, “A 700 GHz single chip balanced SIS mixer”, 16th Int. Symp. Space THz Tech., Gothenburg, 2005.

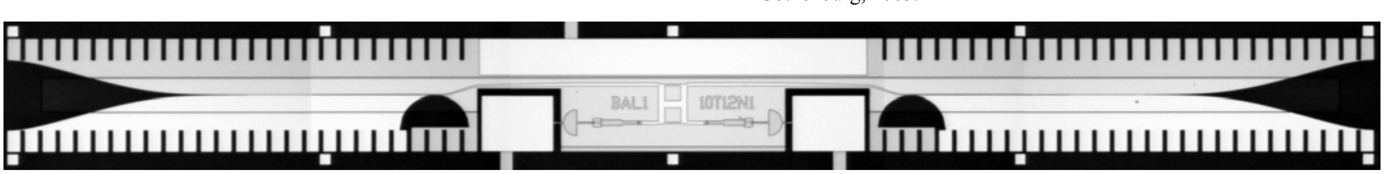

Fig. 17. A 700 GHz single chip balanced SIS mixer, based on back-to-back finline tapers. The RF and LO signals are fed via the two finline tapers and combined in microstrip quadrature hybrid at the center of the chip.