Investigation of the performance of a 700 GHz finline mixer

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Abstract

We report the successful operation of an SIS finline mixer at frequencies above and below the superconducting gap of Nb. The mixer is fed by an antipodal finline taper deposited on a quartz substrate in one piece with the Nb-AlO_x-Nb tunnel junction and Nb tuning circuitry. RF power is coupled to the waveguide mounted finline mixer chip via a Pickett-Potter horn-reflector antenna and the mixer is tuned by a novel three-stage Chebyshev filter and radial stub tuner. We describe the design and testing of the mixer between 640 and 710 GHz, paying particular attention to the evaluation of conduction losses in the finline chip, and the prediction of the conversion gain of the mixer. Our results show that finline mixers can have good performance both above and below the superconducting energy gap.

Introduction

We have previously reported the successful operation of finline based mixers at 230 GHz[1] and 350 GHz[2], and the preliminary testing of a finline based mixer at 700 GHz[3]. We have achieved mixer performance comparable to that of conventional waveguide mixers at low frequencies, but our previous 700 GHz mixer's performance suffered from poor conversion gain, mainly because the particular device tested was tuned above the band of our LO source.

The finline design offers a number of benefits over more conventional designs, including:

- High performance, wide bandwidth mixer feed

(a) Mixer block assembly, with reflector and mouth of horn on right side.

(b) One half of the mixer block, showing Potter horn and IF CPW.

Figure 1: The aluminium split mixer block.

- Simplified mixer block design, as no backshort is required
- Easier handling of the large mixer chip

the latter two of which are particularly pronounced for high frequency designs. In fact, once the RF signal is confined to the microstrip, the mixer is unaffected by changes in, or removal of the surrounding mixer block. The large chip and lack of mechanical tuning also allows the fabrication of devices with integrated RF circuitry such as on-chip image separation circuits[4] and also back-to-back finlines for interferometric operation and on-chip LO coupling, a design we are already testing at 350 GHz[5].

The finline mixer design necessarily includes a length of superconducting transmission line between the mixer feed and the SIS tunnel junction. At frequencies above the superconducting gap, conduction losses in this line will degrade the performance of the mixer. A finline mixer fabricated from a single superconducting material will only work well above the superconducting gap if these losses are small. Although the losses in many transmission lines can be rigorously calculated, most of this transmission line is part of the finline taper, the losses of which cannot easily be analysed by any one rigorous technique. Conventional waveguide probe mixers are also degraded by conduction losses in their superconducting transmission lines and tuning circuits, but it is not clear whether an all-Nb finline mixer can achieve similar or better performance than an all-Nb waveguide probe design above 700 GHz.

Mixer Design

The 700 GHz mixer described here is fed by a Pickett-Potter horn-reflector antenna, a design which ensures a low side-lobe level and high directivity beam, while simplifying mixer block machining[6, 7]. The mixer chip itself comprises an antipodal finline taper, superconducting microstrip, an SIS Nb-AlO_x-Nb tunnel junction and a three-stage, Chebyshev section tuning circuit. The mixer chip is held within slots machined into the sides of the split aluminium mixer block waveguide so that the tip of the finline taper protrudes into the throat of the horn. The mixer chip also has niobium corrugations deposited as part of the finline structure to prevent RF power leaking into the slots holding the chip.

The mixer's IF output is taken from bonding pads on the chip by $50\mu m$ bond wires connected to a ground-backed co-planar waveguide, leading to an SMA connector. The IF signal is then passed through an isolator before being amplified by a cryogenic amplifier, with a noise temperature of $6 - 8K$ across a 4 GHz band centred at 4 GHz.

PPHR Antenna

The mixer described in this paper is fed by a Pickett-Potter horn-reflector (PPHR) antenna, a design chosen to avoid the complexity of machining the large number of deep, narrow grooves required for a corrugated horn at 700 GHz. The Pickett-Potter horn is a dual mode feed employing a single step discontinuity at the throat of a conical horn to excite a small fraction of the TM_{11} mode, in combination with the dominant TE_{11} mode. The horn length and the radii at the step are chosen such that the aperture fields become plane-polarised, similar to the field of a corrugated horn at the design frequency. The circular waveguide feed of the PPHR is gradually transformed to the $320\mu m \times 160\mu m$ rectangular waveguide holding the mixer chip.

We have previously shown[3], using modal matching simulations and experiment, that this design gives similar performance to a corrugated horn-reflector antenna over at least a 15% band (corresponding to a 100 GHz band for a 700 GHz centred feed). In particular, we have used a previous finline mixer chip within the mixer block as an SIS direct detector to make direct measurements of the mixer's beam pattern and cross polarisation levels.

Finline Taper

Radiation from the PPHR antenna is coupled to the mixer chip via an antipodal finline taper, embedded in the waveguide at the throat of the horn. The fins form the base and wiring layers of the tunnel junction and are fabricated from $310nm$ and $400nm$ thick Nb respectively, separated in the region of overlap by $400nm$ of SiO. The whole of the mixer chip structure is deposited on a $60\mu m$ quartz substrate, which has a point extending along the waveguide to provide a smooth transition from empty waveguide to waveguide with

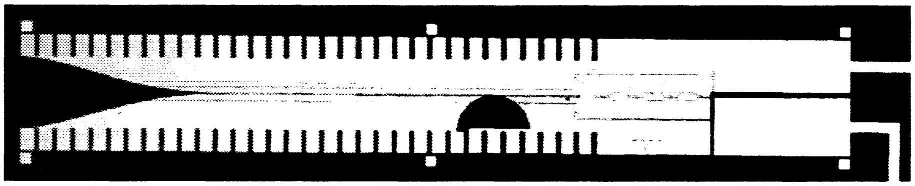


Figure 2: A 700 GHz finline mixer chip. RF signal enters the chip from the left and IF and Bias connections are on the right.

a dielectric across the centre. At the throat of the horn, the finline acts as a unilateral finline, with an impedance of several hundred Ohms. As the fins converge, the impedance is gradually reduced to approximately 50Ω at the point where the fins overlap. Beyond this point, the width of overlap is gradually increased, and when the width is large enough that the fringing effect can be ignored, a transition to 20Ω, $3\mu m$ microstrip takes place. Once the fins begin to overlap, the fields are confined to the planar structure, and so are insensitive to the waveguide geometry. The only accurate machining required in the mixer block, apart from the horn, is the slot which holds the substrate within the waveguide. We have previously reported theoretical methods for the synthesis of finline tapers, and have successfully used these to design feeds for 230 GHz and 350 GHz mixers[1, 2].

Tuning Structure

Good mixer performance requires efficient tuning of the junction capacitance over design bandwidth of the mixer. In our previous designs, at lower frequencies, we have employed single $\lambda/4$ end-loaded stubs for this purpose. At higher frequencies this design is less attractive as the stub length becomes comparable to the junction dimensions, and may also be strongly affected by fabrication tolerances. Consequently we have investigated an alternative tuning mechanism based on a three-stage Chebyshev section and a half moon radial stub RF choke.

Initial design was carried out in a lumped element model using Agilent Design Studio to optimise the length and characteristic impedances of the four microstrip elements of the tuner to give the maximum return loss. However, verification of the resulting design using Sonnet Software Inc.'s "em Suite" software gave significantly different tuning to the lumped element model. This is to be expected as two of the three microstrip sections are substantially wider than they are long, and so the two dimensional nature of the currents in the step regions must considered. The closeness of these steps in microstrip width also make it difficult to obtain the low impedance required for the middle section, thus limiting the bandwidth of the mixer. Further design work was carried out wholly within Sonnet.

The last section of the tuning structure (nearest to the junction) is only $7\mu m$ long. The

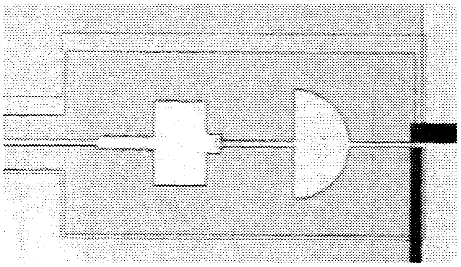


Figure 3: The microstrip tuning structure used on this mixer. RF signal enters down the left hand microstrip and IF signal leaves from the right.

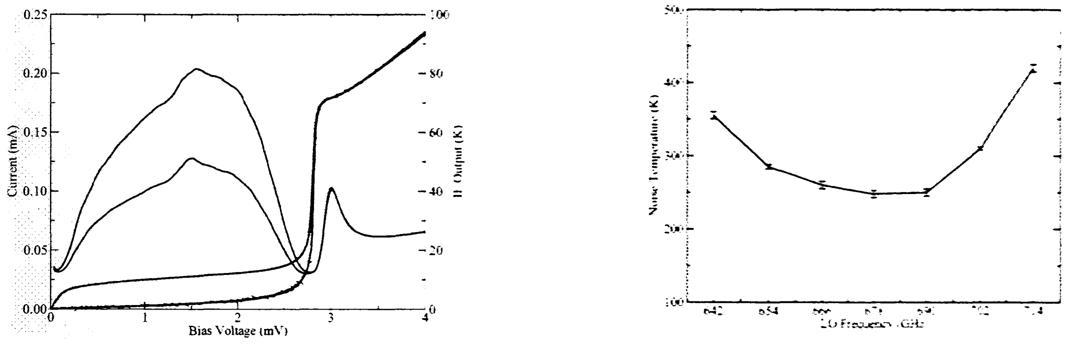
effective length of this section may therefore be altered by fabrication tolerances. Tests in Sonnet with the junction misplaced by up to $0.5\mu m$ have shown significant changes in tuning. However, fabrication tolerances on the junction's characteristic impedance give even greater shifts in tuning.

Device Fabrication

The mixer chip was manufactured by KOSMA, University of Cologne on $200\mu m$ Infrasil quartz. The chip was fabricated in five steps:

- Sputtering of Nb-AlO$_X$-Nb trilayer ($200nm$, $10nm$ and $100nm$ thickness respectively), and lift-off to form the lower finline and ground plane for the tuning circuit
- Junction definition lithography and reactive ion etching of upper Nb layer of trilayer
- Evaporation of first $200nm$ SiO insulation layer
- Evaporation of second $200nm$ SiO insulation layer
- Sputtering of $400nm$ Nb wiring layer and upper finline, with $30nm$ Au protection layer

Two insulation layers are used to allow reliable contact to the junction while achieving the low impedances necessary for the three stage tuning structure. Before mounting in the mixer block the chip is diced to size, the point is diced on the substrate at the mouth of the finline, and the chip is thinned from $200\mu m$ to $60\mu m$.



(a) IV (pumped and unpumped) and IF curves with a 690 GHz LO.

(b) Receiver noise temperature.

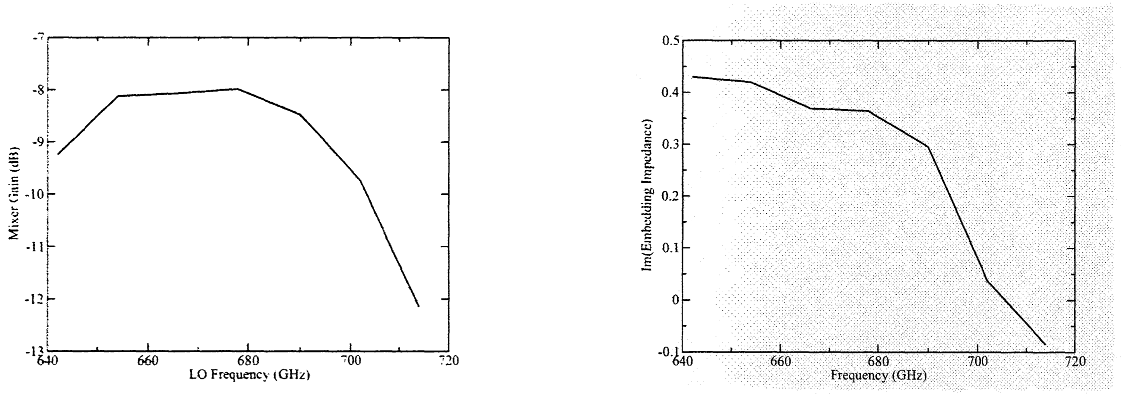
Figure 4: Hot-Cold load mixer test results at 2.5 K.

Results

The particular chip used for these mixer tests was selected on the basis of the Fiske resonance shown by the device during initial dipstick testing, and relatively low leakage current. The voltage biased I-V curve obtained during these tests showed a Fiske resonance at 1.43 ± 0.02 mV, equivalent to 690 ± 10 GHz, with a gap voltage of 2.78 mV, equivalent to 672 GHz.

Mixer tests were carried out at a physical temperature of 2.5 K, achieved by pumping He vapour out of the dewar to reduce the vapour pressure to $\sim$ 200 mBar. Lower temperatures can be achieved with this system, but the performance of the IF amplifier was found to degrade on reducing the temperature to $\sim$ 2.2 K. At 2.5 K the gap voltage of the device was increased to 2.82 mV, equivalent to 682 GHz.

The mixer was tested with a Gunn diode LO using a doubler-tripler multiplier chain, with LO power injected by way of an $8.5\mu m$ mylar beamsplitter. This LO scheme provided sufficient power to pump the mixer between 642 GHz and 714 GHz. In fig. 4(a), we show the DC response of the mixer, both with and without LO power at 690 GHz, as well as the hot and cold load IF output powers. DSB receiver noise temperatures (fig. 4(b)) were measured by the Y-factor method giving a best receiver noise temperature of 250 K, and the mixer conversion gain was calculated (fig. 5(a)), after calibrating the IF output power using the method of Woody.



(a) Mixer gain.

(b) Embedding impedance recovered from pumped IV curves.

Figure 5: Mixer conversion gain and junction embedding impedance calculated from mixer test results.

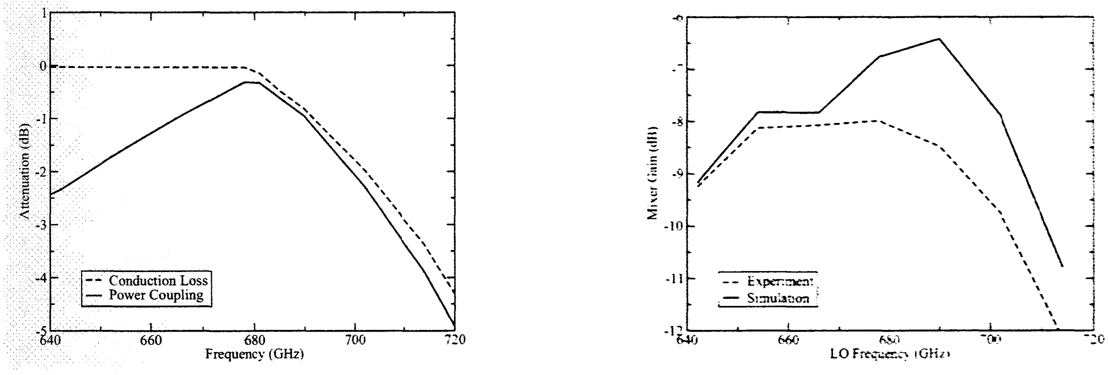
Device Tuning

The embedding impedance seen by the tunnel junction greatly affects the gain of a SIS mixer, and is responsible for the tuning of the mixer. In order to accurately simulate the gain and tuning of the mixer we have attempted to recover the embedding impedances and LO pump levels by matching the pumped IV curve calculated from the unpumped IV curve to the measured pumped IV curve[7]. The calculation of the pumped IV curve is based on our recently reported nonlinear mixer theory[9], with the embedding impedance and LO pump power being varied by a downhill simplex algorithm, until the best match to the measured pumped IV curve is found.

The recovered imaginary part of the embedding impedance is shown in fig. 5(b), and indicates that the mixer is tuned just above 702 GHz. This agrees well with the position of the Fiske resonance.

Simulations

The nonlinear mixer theory, mentioned above, can be used with the embedding impedance results and the measured unpumped IV curve to simulate the gain of the mixer. In order to get results that are comparable with the experimental results we must take into account the losses in the receiver optics and RF circuitry. For frequencies above the superconducting gap (682 GHz) we expect considerable conduction losses from the large amount of Nb transmission line between the mixer feed and the tunnel junction. This is in addition to effective losses due to reflection from the tuning structure at frequencies where there is an



(a) Simulated power coupling and total conduction losses for the tuning circuit.

(b) Mixer gain from simulations and experiment.

Figure 6: Results of simulations of the tuning circuit and mixer gain simulations.

impedance mismatch.

In order to obtain values for both of these contributions to the RF losses, we have simulated the tuning circuit using “em Suite”, a method of moments planar circuit simulator. The simulated circuit included the tuning structure, RF choke and $300\mu m$ of microstrip that connects the finline taper to the tuner, as well as an extra $250\mu m$ of $3\mu m$ microstrip to account for the loss of the finline taper. The surface impedance and conductivity of the niobium used in the circuit was calculated from Mattis-Bardeen theory[10], and an effective junction capacitance of 85 fF was used.

The results from “em” show that the best power coupling to the junction is achieved at 680 GHz, with a loss of -0.3 dB, which increases rapidly on either side of this point, due to poor impedance match on at lower frequencies, and increasing conduction losses at higher frequencies. The portion of the *available* power (after conduction losses) coupled to the tunnel junction is greatest at 690-702 GHz, in agreement with the embedding impedance results above.

The losses in the beamsplitter and $650\mu m$ polythene dewar window were calculated as 0.2-0.4 dB across the LO band using the methods of Goldsmith[11] and subtracted from the simulated gain. An IR filter is also present in the optical path which will give some losses, as will any reflections from the horn and finline taper, although these should be small at 700 GHz, the design frequency of the mixer feed.

The simulated values of the gain agree well with the experimental results at frequencies below the gap, while there is a difference of 1-2 dB above the gap. This difference is probably attributable to an underestimation of the conduction losses in the circuitry. Well below the gap, the conversion gain is fairly low, mainly as a consequence of the narrow tuning of the mixer.

Conclusions

We have designed and tested an all Nb finline SIS mixer over the frequency range 640-710 GHz, fed by a Pickett-Potter horn reflector antenna.

We have been able to recover the embedding impedance and LO power levels of the mixer from experimental data using a fully nonlinear mixer theory, and then used this theory to accurately the conversion gain of the mixer. The predicted and measured gains, which have a typical value of -8 dB, agree very well below the superconducting gap, and within 1-2 dB above the gap. The ability to predict the gain is a key factor in improving the performance of future mixers.

The best measured receiver noise temperature of $\sim$ 250 K was obtained just above the superconducting gap, and is comparable to results published in the literature for more conventional all-Nb waveguide probe mixers[12].

The performance of this mixer confirms that finline mixers perform well at frequencies around the superconducting gap. In combination with the excellent results we have recently obtained using a 350 GHz back-to-back finline receiver as both an interferometer and a mixer where the LO and signal are combined on the chip after being fed by separate finlines, we believe that it should be feasible to make complicated integrated receivers, such as side-band separating mixers, at frequencies at least as high as 700 GHz. As part of our development of finline mixers we are testing devices with the niobium fins replaced by aluminium, in order to understand the losses better. This work will also allow the use of alternative, higher gap superconducting materials while still using Nb-AlO$_x$-Nb junctions. In combination with the simplified fabrication of the Pickett-Potter horn and finline mixer blocks over corrugated horns and waveguide probe mixer blocks, this work should allow complex finline mixers to be designed at frequencies above the superconducting gap.

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