A FULL-BAND WAVEGUIDE SIS RECEIVER WITH INTEGRATED TUNING FOR 75 - 110 GHz

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Abstract

The performance of a broadband SIS receiver with *no* mechanical tuning elements was scale modelled and tested. The mixer mount had a broadband waveguide to microstripline transition consisting of a 4-step Chebychev single ridge transformer. The last step of the ridge connected the waveguide to a microstripline circuit. The on-chip circuit consisted of a microstripline, which transmitted the *rf* and the local oscillator signals to the SIS mixer. Some chips included a thin film strip inductor in parallel with the mixer. Both the SIS element and the inductor had *rf* grounds provided by 90° radial stubs. The inductor tuned out the junction capacitance to allow operation over the full frequency band. The SIS element can be a single junction or series array using Nb/AlO_x/Nb trilayer tunnel junctions with areas as small as 0.5 μm^2 and $V_m(2mV)$ = 39 mV. Preliminary results indicated a DSB receiver noise temperature of 65-80 K across the band measured at 4.4 K with an internal cryogenic *rf* hot/cold source and with T_{if} = 21 K. With another device, we achieved a mixer noise temperature of 35 K at 100 GHz, increasing to 45 K at 79.5 and 110 GHz. Coupled mixer gain of up to +3 dB and negative dynamic resistance on the first photon step were observed. The lowest noise temperature was obtained for an untuned single junction mixer at 80 GHz; T_R = 41 K and T_M = 20 K were measured.

Introduction

SIS (superconductor-insulator-superconductor) tunnel junction mixers have proved to be an attractive technology for receivers in the mm-wave band. In radio astronomy, SIS receivers have in several cases outperformed Schottky receivers in terms of receiver noise temperature and mixer gain.[1,2,3] However, the SIS receivers with the lowest noise and highest gain often have mechanical tuning or a narrow bandwidth.[4,5,6,7] This is a major drawback for the development of focal plane arrays where a large number of imaging elements would have to be tuned individually for every frequency. We have demonstrated a prototype for a single channel of a focal plane array receiver employing an SIS mixer mount with a large instantaneous bandwidth around 100 GHz without mechanical tuning elements.

Mixer Design

Fig. 1 shows a schematic diagram of the mixer mount and the microstripline circuitry. The signal and the local oscillator (LO) were directed through a low loss broad-band WR-10 cross-coupler[8] (not shown) into the input waveguide. A four-step Chebychev single ridge transformer[9,10,11,12] at the end of this waveguide provided a broad-band waveguide-to-microstrip transition (Fig. 1a). The waveguide impedance was transformed to 50 Ω at the last ridge section which made contact to the 50 Ω input microstripline on the chip (position A in Fig. 1b). This section was λ/4 long at 100 GHz to accommodate a further impedance transformation (by changing the width), if needed in the future. The existing impedance transformation by the ridge on the *rf*-side facilitates the use of low impedance SIS junctions which keeps the $\omega R_N C$-product low. This 50 Ω *rf* impedance also eases matching to the intermediate frequency (*if*) amplifier. The base electrode of the SIS junction was connected to the end of the microstripline (pos. B); the counter electrode was connected via a wiring layer to a 90° radial stub (pos. C). A second 90° radial stub, next to the one terminating the SIS element, provided a separate *rf* ground termination for a thin film inductor in parallel with the SIS element. This inductor was used for tuning out the capacitance of the SIS element. The 90° radial stub, like an unterminated quarter wave microstripline, provides a broadband *rf* ground at a well defined point close to its apex[13,14,15] and gives an open circuit for the *dc*-bias and *if*-signal. The use of radial stubs is a practical way of providing *dc*- and *if*-isolated broadband *rf*-ground terminations at nearly the same geometrical location. Note that the parallel tuning inductor in our design did not short the *dc*-bias and the *if*-signal.

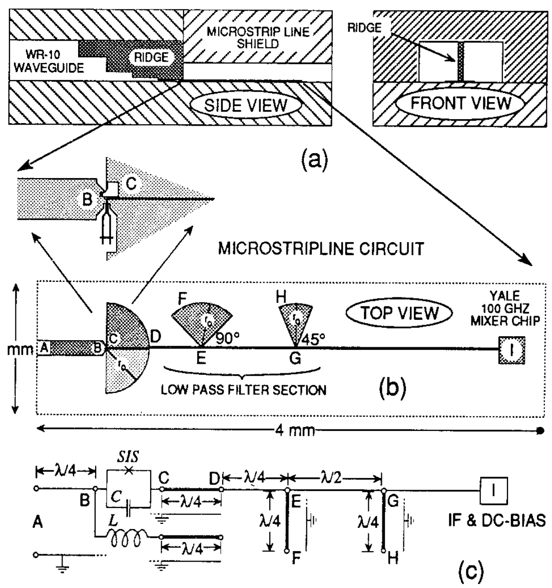

Fig. 1. Schematic diagram of the mixer mount. a) Side views of the ridged waveguide Chebychev transformer and the mixer chip. b) Microstripline circuit with a detail of the SIS element. c) Simplified electrical equivalent of the microstripline circuitry.

A low-pass filter (D-I in Fig. 1b) was connected to the periphery of the SIS-radial-stub to *dc*-bias the SIS element and transmit the *if*-signal. In a similar way, another low-pass filter line could be connected to the second radial stub for biasing circuits such as a local oscillator (Josephson,[16] soliton,[17] or flux-flow[18]) or a Josephson tuning inductor.[19]

Scale Modeling

Scale modeling of the ridge transformer, microstrip circuit, and entire mount was done at 2 - 8 GHz with a 28.4 times larger mount. With a 50 Ω chip resistor in place of the SIS element, the VSWR was lower than 1.38:1 for frequencies corresponding to 74 - 114 GHz in the actual mount. With a chip capacitor of 1 pF (equivalent to 35 fF in the actual mount) in parallel with the 50 Ω chip resistor and a copper wire inductor coupled to the second radial stub, the VSWR was less than 2.1:1 for the 75 - 107 GHz band.

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Junction Fabrication

$Nb/AlO_x/Nb$ trilayer tunnel junctions were fabricated with areas as small as 0.5 μm^2, current densities up to 5000 A/cm^2, and *average* V_m values of 39 mV (at 2 mV, 3000 A/cm^2, and 4.4 K). The $\omega R_N C$ product for these devices is ~ 1.2 to 2. The trilayers were deposited and patterned at the Westinghouse Science and Technology Center.[20] A modified SNIP technique was developed to produce these small junctions. The individual chips were fabricated on 25.4 x 25.4 mm^2 large and 50 µm thick fused and crystal quartz wafers.[21] 15 different configurations and in total 102 mixer chips were fabricated on each wafer. Single SIS junctions and series arrays of up to 12 junctions with individual junction areas of 0.5 μm^2 up to 4 μm^2 were included in the designs.

Dewar and Receiver Measurements

The receiver system (see Fig. 2) was built to determine the noise temperatures of the receiver (T_R) and the mixer (T_M), the coupled and available gain of the mixer (G_M and G_A), and the *if*-system noise temperature. Similar receiver configurations have been used before.[5,22] A vacuum dewar with a 254 mm diameter coldplate[23] was furnished and complemented with the mixer mount, *if*-system, and control circuitry. An internal cold circulator and a directional coupler were used to measure the *if* mismatch of the mixer, the mixer gain, and the *if*-system gain. A cryogenic 50 Ω coaxial *if* hot/cold load was built and used to determine the *if* noise temperature. With a coaxial switch,[24] the cryogenic *if*-amplifier could be connected to either the mixer output, a cold 50 Ω termination, the hot/cold 50 Ω termination, or a short circuit for calibration in the *if*-mismatch measurements. An internal *rf* hot/cold load was developed to accommodate fast and reliable optimization of the receiver noise temperature. It consisted of a WR-10 waveguide with a heated silicon vane that could be moved in and out through a 0.36 mm wide slot, and a cold waveguide termination behind the vane. The part of the vane that was inserted into the waveguide was etched down to 14 µm. An ~80 nm thick NiCr resistive layer was deposited on one side of the vane. The heaters and thermometers were mounted on the thicker part of the vane (d~360µm). By bringing the vane in and out of the waveguide with two electromagnets, the hot vane and the cold termination could alternatively be presented to the mixer. To reduce the error due to impedance mismatches, the vane was left in the waveguide and used as both the hot and the cold source while taking data. Our *LO* source was a YIG-oscillator[25] which was tripled to 79.5 - 120 GHz with a multiplier[8] circuit.

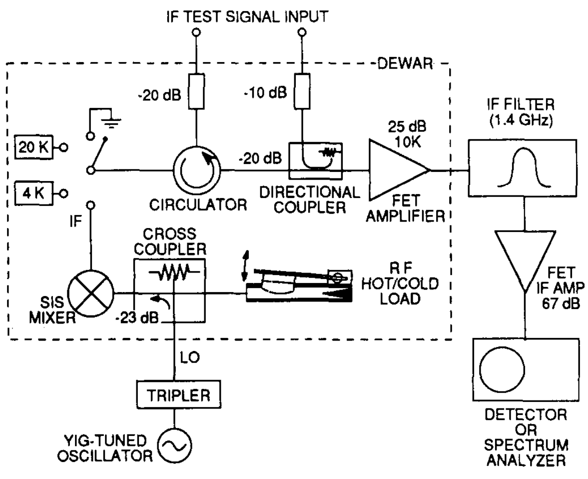

Fig. 2. Schematic diagram of the receiver set-up. Components inside the dashed line were mounted on the cold plate; components outside were at room temperature.

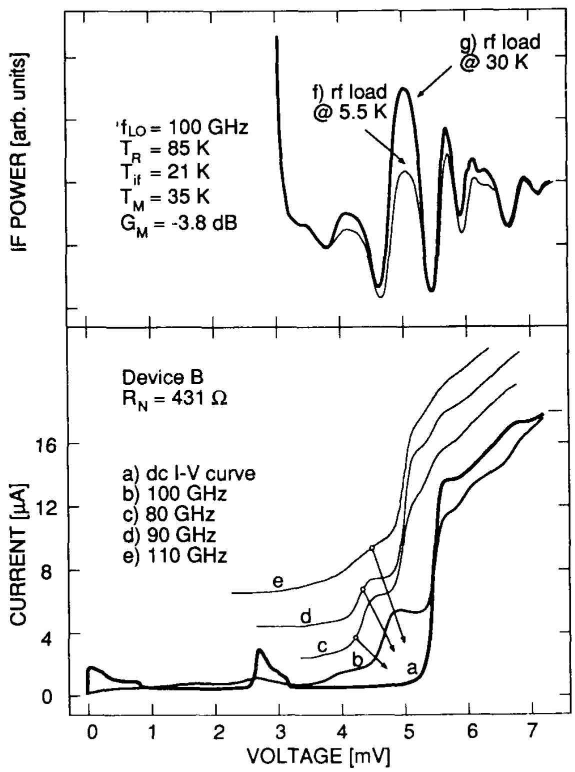

Fig. 3. Current and *if* power vs. voltage characteristics of device B. This device was a 2 junction series array and was inductor tuned. Curves b-e have been offset as indicated by the arrows.

Results

Fig. 3 shows a typical current-voltage (I-V) curve of a 2 junction array (curve a). Curves b-e show the I-V curve when the LO is applied for different frequencies. A high dynamic resistance on the plateau of a step is usually associated with a good *rf* match. According to theory,[26,27] for certain source admittances, negative dynamic resistance and conversion gain could be obtained for these very non-linear devices. This has been observed for SIS mixers employing mounts with mechanical tuning elements and narrow instantaneous bandwidths.[7,28,29,30,31] For several of our mixers, we observed negative resistance across a fairly wide band. Coupled conversion gain (DSB) up to +3 dB was also observed (see Tab. I). Fig. 4 shows G_M and T_M values as a function of frequency for several devices. The results for T_R are comparable to recent results from NRAO.[32] However, we have higher mixer gain and somewhat higher mixer noise temperature. In the NRAO measurements, noise contributions which arise in coupling the signal from outside the dewar are included in T_R. The calculations using Tucker's theory[27] that were done for some of our devices overestimated the gain and underestimated the noise, when compared with the experimental results (see device I in Fig. 4 and devices E and I in Tab. I). In the calculations, we used source admittances that were obtained by fitting theoretical I-V curves to the experimental ones.[33,34] This method could be a potential source of errors in determining the source admittances. Other possible reasons for the discrepancies between theory and experiment could originate from an impedance mismatch to the *rf* hot/cold vane, which would deteriorate the apparent receiver performance. Resistive losses in the 4-step single ridge Chebychev transformer could also impair the performance. These issues need to be investigated before we can draw any strong conclusions on the differences between the experimental results and the theoretical calculations.

Table I. Summary of the data and results from our measured SIS mixers.

Mixer element	f_{LO} [GHz]	T_R^{DSB} [K]	T_M^{DSB} [K] exp	T_M^{DSB} [K] theor	G_M^{DSB}[dB] exp	G_M^{DSB}[dB] theor
Device A 1 jcn 0.5μm^2 $R_N = 71\ \Omega$ Untuned	80	41	20		-3.0	
	100	202	39		-10	
Device B	80	141	49		-6.4	
2 jcns 0.5μm^2 ea	90	118	40		-5.7	
$R_N = 431\ \Omega$	100	85	35		-3.8	
Inductor tuned	110	165	46		-7.5	
Device C	80	79	64		+1.5	
2 jcns 0.5μm^2 ea	90	76	59		+0.9	
$R_N = 125\ \Omega$	100	65	54		+3.0	
Inductor tuned	110	80	61		+0.4	
	120	114	75		-2.7	
	80	125	60	21	-7.2	-5.5
Device E	85	119	61	22	-6.7	-5.7
4 jcns 0.5μm^2 ea	90	158	82	23	-7.9	-5.7
$R_N = 619\ \Omega$	95	136	72	26	-7.1	-6.2
Untuned	100	136	69	24	-7.3	-5.9
	105	136	69	23	-7.3	-5.9
	110	173	83	-	-8.6	-
	80	104	62	22	-5.5	+0.3
Device I	85	65	44	17	-2.5	+2.0
4 jcns each 4μm^2	90	73	52	21	-2.5	+2.8
$R_N = 124\ \Omega$	95	64	47	28	-1.5	+2.2
Inductor tuned	100	66	43	32	-2.9	+0.4
	105	87	44	31	-5.6	-1.1
	110	127	49	65	-8.2	-5.6

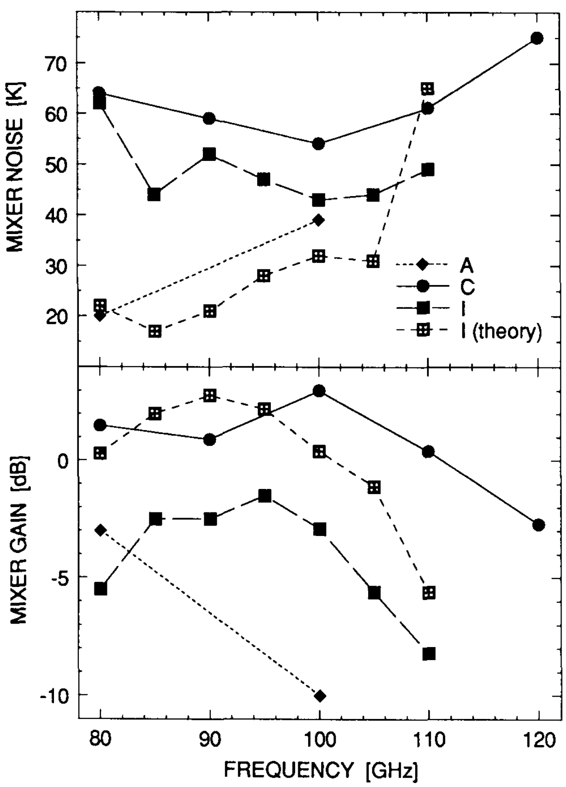

Fig. 4. Mixer noise (upper graph) and mixer gain (lower graph) vs. frequency for devices A, C, and I. Theoretical predictions are also plotted for device I.

Conclusions

We have demonstrated a full-band (75 - 110 GHz) low-noise SIS receiver with integrated tuning. There are no mechanical tuning elements in the design. Coupled gain to the 50 Ω *if-* amplifier of up to 3 dB (DSB) was obtained. No impedance transformers were used on the mixer output.

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