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AN SIS MIXER FOR 85-116 GHZ USING INDUCTIVELY SHUNTED EDGE-JUNCTIONS

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ABSTRACT

For the most part, SIS receivers have failed by a wide margin to achieve the sensitivity promised by theory. One of the main reasons for this is the difficulty of providing appropriate embedding impedances at the signal and image frequencies as well as the higher harmonic sidebands. We describe an SIS mixer with a broadband integrated tuning structure. The mixer is tunable from 85-116 GHz, and at midband has a noise temperature of 6 ± 6 K DSB and unity DSB conversion gain. Referred to the mixer input flange, the receiver noise temperature is 9 ± 6 K at midband.

INTRODUCTION

Since the first reports of its successful use in 1979, the superconductor-insulator-superconductor (SIS) tunnel junction mixer has been recognized as the best front-end for low noise millimeter-wave receivers. This is a result of the extremely low shot-noise, potential conversion gain, and low local oscillator power requirements of SIS mixers. Currently, about ten SIS receivers, operating from 43 to 290 GHz, have been reported in use on radio telescopes around the world, although most of these have sensitivities little or no better than their main competitor, the Schottky-diode mixer receiver [1].

We believe the main reason that SIS receivers have been slow to develop their full potential is the difficulty of providing appropriate embedding impedances at the signal and image frequencies as well as at the higher harmonic sidebands $nf_{LO} \pm f_{IF}$. The harmonic sidebands should probably be short-circuited for best performance, and this is readily accomplished by using SIS junctions with relatively large capacitance. This capacitance must then be tuned out over the signal and image band, which can be difficult to accomplish [2-5].

In the present paper we describe an SIS mixer with an integral tuning structure consisting of a short two-wire transmission line stub with a quarter-wave superconducting transmission line as a DC and IF block. The mixer has a double sideband (DSB) noise temperature of 6 ± 6 K and unity DSB conversion gain at midband, and is tunable from 85-116 GHz.

DESIGN OF THE INDUCTIVELY SHUNTED JUNCTIONS

In principle, a lumped inductance connected across an SIS junction could be used to tune out the junction capacitance. This inductance requires a DC block if it is not to short-circuit the junction at DC and IF. In a practical mixer, additional fixed and adjustable tuning elements may be needed to couple efficiently between the waveguide and the junction over a reasonable tuning range.

A simplified diagram of an inductively-shunted two-junction array, and its equivalent circuit, are shown in Fig. 1. The junctions are shunted by an electrically short two-wire transmission line stub (loop) whose inductance is determined by the length l. The inductance L_2 is that of the two-wire stub. L_1 is the series inductance of the array itself and should be kept small to avoid an impedance transformation between the small-signal junction resistance R_j and the external circuit. L_x is the inductance of the leads to the external circuit, and depends on the structure in which the inductively shunted junction is mounted (e.g., whether a waveguide, stripline, or quasi-optical mount is used). The quantity M is the mutual inductance between the inductive loop and the array of junctions. For the mixers reported here, scale model measurements show that L_1 and M are small enough not to affect

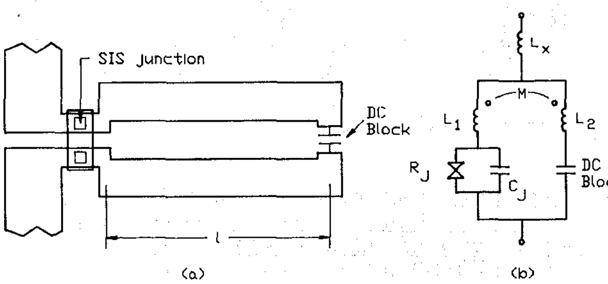

FIG. 1(a). Simplified diagram of an inductively-shunted two-junction SIS mixer. The tuning inductor is a short parallel strip transmission line with an RF short-circuit at its right end. (b) Equivalent circuit.

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the design substantially; however, this is not always the case, particularly when longer arrays are used or at high frequencies [5,6].

The configuration of the SIS junctions, tuning inductor, and DC block used in the present work is shown in Fig. 2(a). The DC block may consist of a lumped capacitor, as depicted in Fig. 1(a), but there are certain complications with this approach. Unless the capacitance is much greater than the array capacitance, the RF bandwidth is reduced. However, it is often difficult to fabricate a sufficiently large capacitor with electrically small dimensions because the propagation velocity in the region between two superconducting capacitor plates separated by a thin dielectric layer of high relative dielectric constant can be less than 10% of the free-space velocity. A second possible disadvantage of the simple lumped capacitor DC block is its effect on the IF circuit. If the capacitance of the block is chosen to be large compared with that of the SIS array it may not be negligible at the IF. By using the quarter-wave stub DC block described below, these disadvantages are largely overcome.

The DC block consists of two quarter-wave parallel plate transmission line stubs formed on top of the legs of the tuning inductor. (Two stubs are used for convenience of fabrication.) The upper conductors of the stubs are connected by the "shorting bar" whose position determines the total inductance. Operation of the circuit is most easily understood in terms of an approximate

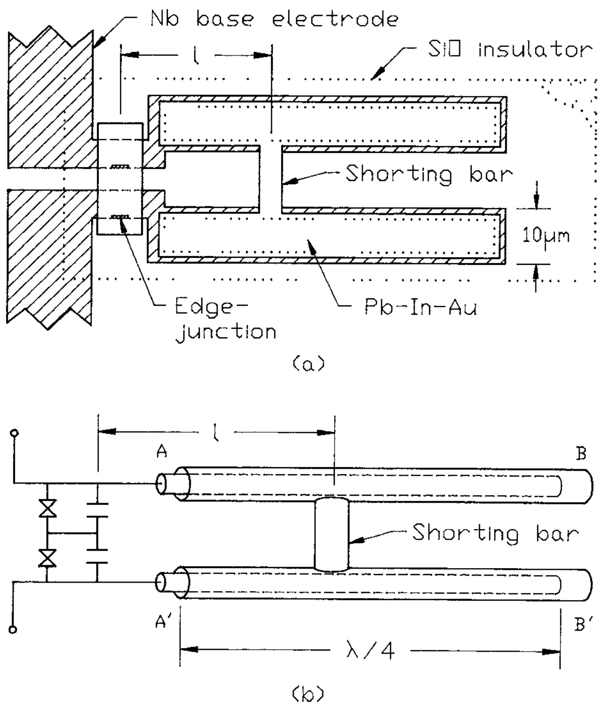

FIG. 2(a). Diagram of the SIS junctions and tuning circuit, approximately to scale. The tuning inductance is defined by the length l. The superconducting parallel-plate quarter-wave DC blocks are 11.6 times shorter than a free-space quarter-wavelength. (b) Conceptual (approximate) equivalent circuit using coaxial quarter-wave stubs.

equivalent circuit, Fig. 2(b), in which the parallel-plate quarter-wave stubs are replaced with coaxial stubs. The open circuit presented to the coaxial line at B is seen as a short circuit at the other end, A. The current flowing around the tuning circuit transfers from the coaxial center conductor (Nb base electrode) across the virtual short circuit at A to the outer conductor (Pb-In-Au upper conductor), and completes the loop via the shorting bar and the virtual short circuit at A'. Because of the unique properties of superconducting transmission lines, it is possible to make a low loss parallel-plate quarter-wave stub with very low characteristic impedance. Its physical length is many times smaller than a free-space quarter wavelength. Using a 70 nm thick Nb_2O_5 dielectric, the high dielectric constant ($\epsilon_r = 29$) and the penetration of the magnetic fields into the superconductors result in a velocity slowing factor of 11.6. For operation at 110 GHz, the quarter-wave stub length is only 59 μm. In the present design the characteristic impedance is 1.8 ohms, and reactance of the stub is less than 1 ohm over almost a 2:1 bandwidth.

FABRICATION OF THE SUPERCONDUCTING CIRCUIT

The edge junctions, tuning inductor, and DC block were fabricated using the Nb/Pb-alloy technology developed at IBM [7]. The major steps in the process are:

(i) Electron beam evaporation of a 230 nm thick Nb base electrode onto a room temperature 0.015-in thick oxidized Si substrate.
(ii) Anodization in areas defined by a photoresist pattern to form 75 nm of Nb_2O_5, leaving 200 nm of Nb.
(iii) CF_4/O_2 RF plasma etching of the Nb/Nb_2O_5 bilayer using a photomask, forming 45° edges.
(iv) Definition of junction windows over the Nb edges by evaporating 275 nm of SiO and liftoff.
(v) Ar RF plasma sputter preclean, Ar/CH_4 RF plasma growth of an NbC_xO_y diffusion barrier, Ar/O_2 RF plasma oxidation to grow the tunnel barrier, and electron beam evaporation of the Pb-In-Au counterelectrode, all with the counterelectrode photoresist stencil in place.
(vi) Ar RF sputter preclean and evaporation of Au bonding pads.

After processing, the wafer was cut into individual 0.005 x 0.010-in. mixer chips which were soldered onto the larger stripline circuit of the mixer.

DESCRIPTION OF THE MIXER

The new circuit was tested using the NASA/GISS type-D mixer mount [8,9], shown in Fig. 3. This mount contains two adjustable short circuits which can provide the junction with a wide range of embedding admittances at a given frequency. The SIS chip is soldered to the larger suspended stripline circuit which crosses two quarter-height WR-10 waveguides. The upper waveguide (in Fig. 3) is

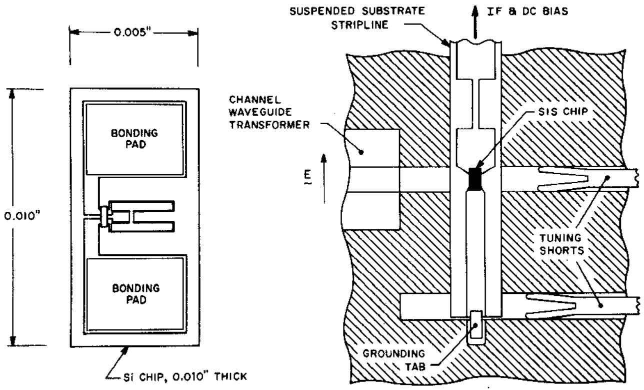

FIG. 3. Diagram of the SIS chip, and a cross-sectional view of the mixer block.

connected on one side to the full-height input waveguide via a channel waveguide transformer [10], and terminated on the other side in a sliding short circuit. The lower waveguide is terminated in a second sliding short circuit to provide an additional degree of tuning. (The waveguide widths are actually 0.096", which is 0.004" narrower than standard WR-10, to permit operation slightly above the normal band without evanescent mode resonances in the mount.) A detailed description of the mixer mount is given in [9].

EXPERIMENTAL RESULTS

In order to evaluate the properties of the mixer, a specially designed test receiver was used. A diagram of the receiver is shown in Fig. 4. This arrangement allows us to determine the conversion loss L_c and noise temperature T_m of the mixer entirely from noise measurements.

The noise temperature of the L-band IF section, measured by switching between the internal hot and cold loads, is 3.2 K at 4.2 K physical temperature, and 2.9 K at 2.5 K physical temperature. (At 1.4 GHz the HEMT IF amplifier itself [11] has a noise temperature of 1.9 K at physical temperatures of both 4.2 K and 2.5 K.)

The receiver can be tuned for either double sideband or single sideband response. Our method of measurement is a variation of that described by Trambarulo and Berger [12]: In our test receiver, T_{IF} can be changed by injecting noise through the IF directional coupler toward the HEMT amplifier. The overall receiver noise temperature T_r is measured using room temperature and 77 K black bodies in front of the room temperature feed horn. Using this method, L_c and T_m can be determined with an accuracy better than 0.2 dB and 6 K, respectively. Almost all the uncertainty arises from the estimation of the temperature and loss distribution along the RF input waveguide.

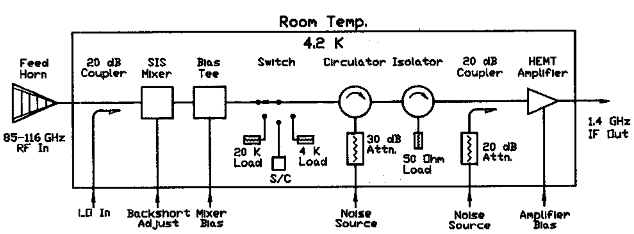

FIG. 4. Block diagram of the laboratory test receiver.

The measured I-V curve of a pair of junctions is shown in Fig. 5 with and without LO power applied. It is significant that, despite the relatively soft (unpumped) I-V curve, we were easily able to tune the mixer for horizontal steps on the pumped I-V curve. This was the first indication that the tuning circuit was performing properly.

Fig. 6 shows the measured DSB receiver noise temperature as a function of frequency. Also shown are several SSB results for which the mixer was tuned to reject the image by ≥ 20 dB, and some results with the receiver cooled to 2.5 K by reducing the pressure in the helium tank. These results are raw receiver noise temperatures measured at the room temperature horn and contain no corrections for the losses in the horn or input waveguide.

At a LO frequency of 114 GHz and 2.5 K physical temperature, the mixer noise temperature and conversion loss deduced from the receiver measurements were: Tm = 6 ± 6 K DSB, and L_c = 0.0 ± 0.2 dB DSB (i.e., unity gain). No corrections for IF or RF impedance mismatches have been made to these figures- i.e., L_c is the transducer conversion loss.

We have measured the saturation characteristics of the receiver using both CW and broadband noise sources. With the mixer tuned for DSB operation, a gain compression of 1 dB was measured for a CW input power of 1.4 nW. This result is in reasonable agreement with the approximate theoretical analysis of noise in SIS mixers given in [13]. With a broadband noise source 1 dB gain compression occurred at a source temperature of 3800 K. The saturation measurements will be more fully discussed in a future paper [14].

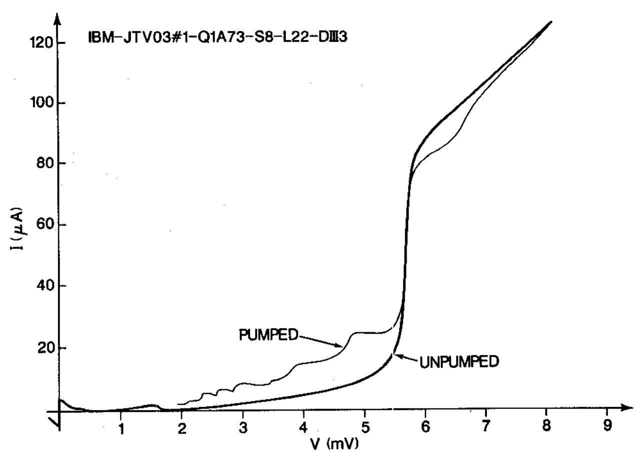

FIG. 5. DC I-V curves with and without LO power applied to the mixer. These curves were measured at 2.5 K with the LO at 113.9 GHz.

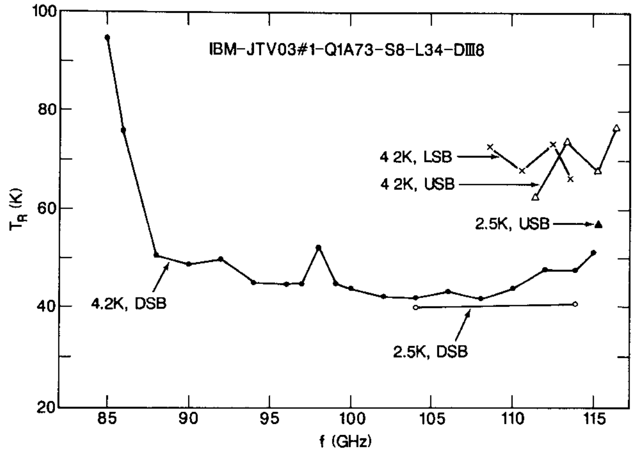

FIG. 6. Overall receiver noise temperature as a function of frequency. Measurements were made at 2.5 K and 4.2 K, and with the mixer tuned for DSB operation or SSB operation in the upper or lower sideband (USB or LSB) as indicated. For all SSB measurements the image response was ≥ 20 dB below the signal response. At 2.5 K the IF noise temperature was 2.9 K. Typical LO power was 20 nW referred to the input flange of the mixer. The noise temperature scale indicates T_r (DSB) for DSB results and T_r (SSB) for SSB results.

DISCUSSION

Despite the relatively soft I-V curves of the two-junction arrays used in these mixers, low mixer noise temperature and conversion loss were achieved, and the mixers tuned easily over 85-116 GHz. The rapid increase in receiver noise temperature below 88 GHz is due to the cutoff of the channel waveguide transformer [10]. Referred to the mixer input flange, the receiver noise temperature is 9 ± 6 K DSB which is within a factor of 2 ± 1 of the photon noise temperature hf/k.

The relatively low saturation power of the SIS mixer compared to conventional semiconductor mixers may restrict its use for some applications. The present receiver is acceptable in this respect for most astronomical observations; however, its (1 dB) saturation temperature (3800 K) will not allow observation of the sun (6000 K) without special calibration procedures. As the saturation power (or temperature) of an SIS mixer is proportional to the square of the number of junctions [1], an immediate solution to this problem is to use arrays of more than two junctions.

We believe that integrated tuning circuits such as the one described in this paper will allow future SIS receivers with wide tuning ranges and sensitivities approaching the ultimate quantum noise limit to be reproducibly fabricated.

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