Progress on Tunerless SIS Mixers for the 200–300 GHz Band

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Abstract—**Hitherto, the best superconductor-insulator- superconductor (SIS) receivers have used one or two waveguide tuners to adjust the embedding impedance of the mixer. An integrated SIS mixer for the 200–300 GHz band with no adjustable tuning is described. A waveguide input is coupled to a coplanar mixer circuit with six individually tuned SIS junctions in series. Using the best mixer, the receiver noise temperature is 45–80 K DSB over 215–275 GHz. The mixer noise temperature at 230 GHz is 12 K DSB, and the conversion loss is 2.5 dB DSB.**

I. Introduction

Coplanar and microstrip superconductor-insulator-superconductor (SIS) mixer designs have given promising results at 100 GHz [1], [2], but have not yet approached the performance of the best mechanically tuned SIS mixers [3], [4]. In this letter, we describe an integrated SIS mixer for the 200–300 GHz band, similar in concept to the coplanar mixer described in [1], with performance comparable to the best tunable mixers in the same band. A coplanar circuit allows a much thicker substrate than is possible with a microstrip circuit if higher modes and troublesome parasitic reactances are to be avoided.

II. Mixer Design and Fabrication

Figs. 1 and 2 show the configuration of the mixer. For operation in the band 200–300 GHz, of interest to radio astronomers, the critical dimensions of the mixer block were scaled by a factor of 0.37 from the WR-10 design of [1]. The mixer was designed according to the procedure described in [3]. The RF source impedance, R_S, and IF load impedance were chosen, for convenience, as 50 ohms. For junctions with a given J-V curve (J is the current per unit area), it is then possible to predict a desirable normal resistance R_N for which the mixer noise temperature is near its minimum, the conversion loss is close to unity, and the input VSWR $\lesssim 2$. For typical Nb–Al-Al_2O_3–Nb SIS mixers, this optimum value[1] of $R_N = 2.4R_S(100/f(\text{GHz}))^{0.72}$. Accordingly, in the present design, $R_N = 62$ ohms. At 250 GHz, a critical current density $J_C = 4500$ A/cm^2 and a specific capacitance $C_S = 45$ fF/μm^2 [5] gives $\omega R_N C \simeq 3$ (the exact value depends on the amount of stray capacitance), and requires an effective (single) junction area of 0.64 μm^2 to give the desired value of R_N. The choice of $\omega R_N C \simeq 3$ is larger than the value of 1.6 suggested in [3] partly to avoid junctions too small to be reliably fabricated using the present process, but also to prevent the inductive junction tuners becoming too long, thus increasing the size of the hole required in the ground plane and its associated inductance which appears in series with the junctions. In this design, we used six junctions in series, each with an area of 3.9 μm^2 (diameter 2.2 μm).

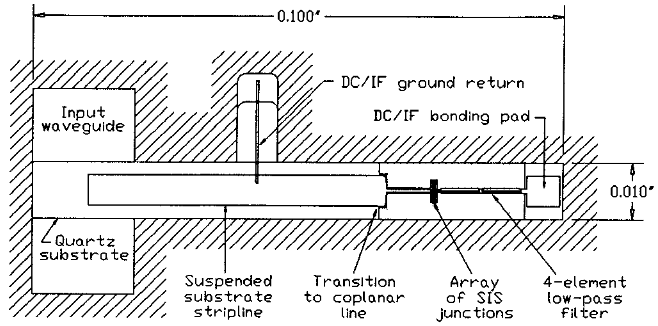

Fig. 1. Complete mixer, showing the waveguide to suspended stripline transducer, dc and IF ground return stub, and the coplanar mixer circuit. The quartz substrate is 0.100-in × 0.010-in × 0.0035-in thick.

In designing the integrated tuning circuits for the individual junctions (Fig. 2), it was found that the (nominally) quarter-wave open circuit stub could be shortened considerably with only a small effect on the embedding impedance, provided the length l_L of the higher impedance line (the inductor) was slightly increased to compensate.[2]

The Nb–Al-Al_2O_3–Nb trilayers were deposited on z-axis crystal quartz wafers 0.010-in thick using a process similar to that described in [5], [6]. However, during Nb deposition, the dc magnetron power was held constant while the Ar pressure was adjusted to maintain constant current. This results in a constant deposition rate and uniform film stress from wafer to wafer over the life of the sputtering target. After dicing the finished wafer into individual mixers, each mixer was waxed facedown and ground to 0.0035-in thick using a dicing saw as a surface grinder.

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[1] In [3], it was found that $R_N = 2.5R_S$ (100/f(GHz)). A more accurate mixer analysis, including five small-signal sidebands, has since shown that a better approximation is: $R_N = 2.4R_S$ $(100/f(\text{GHz}))^{0.72}$.

[2] The MMICAD microwave integrated circuit design program was used for circuit simulation and optimization. MMICAD™ is a registered trademark of Optotek, Ltd., Kanata, ON, K2K-2A9 Canada.

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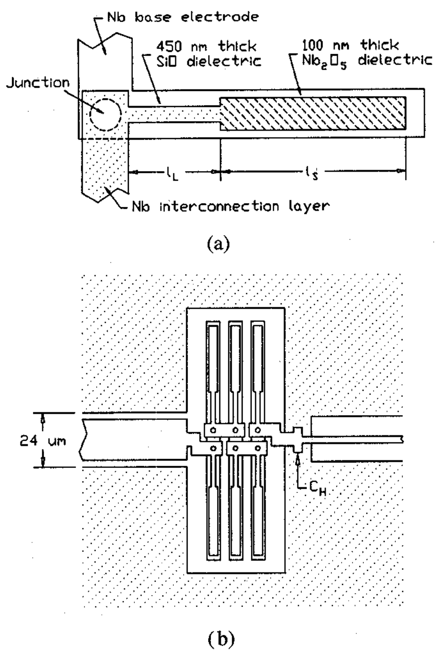

Fig. 2. (a) Details of an inductively tuned SIS junction. (b) Array of six inductively tuned junctions connected to the coplanar input line. The inductance of the hole in the ground plane in the vicinity of the array is tuned out by the capacitor C_H.

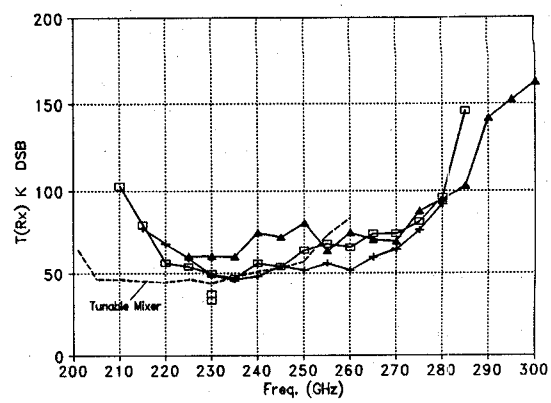

Fig. 3. DSB receiver noise temperature (measured outside the vacuum window) for three mixers from two different wafers. Also shown (dashed) for comparison is the noise temperature of a receiver using an NRAO 401 mixer with two mechanical tuners. Points (▲) and (□) in Fig. 3 (but not the two isolated points (□) at 230 GHz) were obtained with the LO level reduced sufficiently to eliminate Josephson effects. Points (+) were obtained at normal LO level but with increased bias voltage. The pair of isolated points (□) at 230 GHz were obtained at normal LO power and with the mixer biased near the middle of the first photon step. All measurements were made at 4.2 K.

III. Experimental Results

The mixers were tested in a liquid helium cooled vacuum cryostat [7] containing 4.2 K IF calibration components, similar to that described in [8]. The incoming RF signal enters the cryostat through a mylar film vacuum window supported by polystyrene foam [9]. It passes through a PTFE infrared filter at 77 K, and enters a scalar feed horn at 4.2 K. LO power is injected through a 20 dB branch-line coupler, also at 4.2 K. A 1.39 GHz IF was used, and all measurements were made with a 50 MHz bandwidth. The IF noise temperature, including a coaxial switch, two isolators, and a directional coupler, was 6.4 K. No IF impedance transformer was used, and no external magnetic field was applied to the mixers.

Using a chopper wheel to switch the input beam between room temperature and 77 K loads, and a Y-factor meter synchronized to the chopper wheel, the LO power and mixer bias voltage were adjusted for minimum receiver noise temperature. Fig. 3 shows the DSB receiver noise temperature as a function of frequency for three mixers from two different wafers, and, for comparison, the corresponding results for an NRAO type 401 mixer with two mechanical tuners [3]. At the higher end of the frequency band it was found that, for normal LO power levels, structure appeared on the pumped I–V curve and the receiver output became unstable, indicating interference from Josephson currents. This Josephson interference could be reduced either by biasing closer to the gap voltage or by reducing the LO power. The points (▲) and (□) in Fig. 3 (but not the two isolated points (□) at 230 GHz) were obtained with the LO level reduced sufficiently to eliminate Josephson effects. The points (+), were obtained at normal LO level but with increased bias voltage. The pair of isolated points (□) at 230 GHz, were obtained at normal LO power and with the mixer biased as usual near the middle of the first photon step. Despite the apparently better receiver noise temperature at the two isolated points (□), we believe operation in the presence of Josephson interference is undesirable because of the likelihood of nonlinear response and nonheterodyne detection. Furthermore, when sharp features are present on the photon steps of the pumped I-V curve, the mixer gain also shows sharp variations with bias. The dynamic range of the receiver is likely to be reduced as the IF voltage excursions become comparable with the width of the gain peak [10], [11].

The properties of the mixers were deduced from the measured IF output power from the receiver with hot and cold RF and IF loads [8]. For the three mixers (+, □, and ▲) in Fig. 3, at 230 GHz, L =0.9 dB, 2.5 dB, and 2.6 dB DSB, T_M =17 K, 12 K, and 21 K DSB, and the IF output impedance R_{IF} =490, 235, and 250 ohms, respectively.

IV. Discussion

The pronounced rise in the receiver noise temperature at higher frequencies is partly inherent in the present circuit design, and partly a result of the need to operate with lower LO levels at higher frequencies if Josephson interference (previously mentioned) is to be avoided. In the future, we plan to use a magnetic field to suppress Josephson currents in the junctions, which should eliminate the need to operate with reduced LO power.

At low frequencies, the mixers were limited by an apparent biasing instability. This is understood in terms of the RF embedding admittance (seen by the junction conductance), which becomes inductive at the low end of the band. Under this condition, a single SIS junction can exhibit negative dc (and IF) output conductance. For a series array of junctions, it is suspected that this can be an unstable situation in which the individual junctions become unequally biased, and ultimately reach one of a number of possible stable dynamic states in which the junctions remain unequally biased. As we have seldom seen this bias instability in tunable mixers using similar arrays of individually tuned SIS junctions, we surmise that it can be avoided by appropriate design of the embedding admittance as a function of frequency. We are now developing a new tunerless mixer designed to prevent this difficulty.

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