A FULLY INTEGRATED SIS MIXER FOR 75-110 GHz

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ABSTRACT

This paper describes an integrated SIS mixer with low noise over the full 75-110 GHz (WR-10) waveguide band. The mixer uses Nb/Al-Al_2O_3/Nb trilayer technology on a fused quartz substrate. It has no adjustable tuning elements, and the design is suitable for integration with other planar components.

INTRODUCTION

SIS mixers are now well established as the prime choice for ultra-sensitive millimeter-wave receivers. At present, the best SIS mixers use waveguide-mounted SIS junctions and mechanical tuners which limit the bandwidth to a fraction of a full waveguide band. Such designs are not suitable for large scale applications such as NRAO's proposed 40-antenna Millimeter Wave Array, nor for use in space or incorporation into more highly integrated systems. This paper describes an integrated SIS mixer with low noise over the full WR-10 (75-110 GHz) waveguide band. The mixer uses the well established Nb/Al-Al_2O_3/Nb trilayer technology. It has no adjustable tuning elements, and the design should be easy to integrate with other planar components in developing more fully integrated receivers.

APPROACH

Inductively tuned junctions

The high capacitance of SIS junctions requires the use of an integrated tuning circuit if optimum mixer performance is to be achieved without external tuners. At 100 GHz, parasitic inductance in a series array of SIS junctions makes it impractical to use a single inductor to tune out the capacitance of the whole array; rather, each junction needs its own tuning circuit [1]. The configuration used in the present mixer is shown in Fig. 1. The inductor which tunes out the junction capacitance is a short parallel-plate transmission line. To avoid short-circuiting the junctions at DC and IF, a quarter-wave superconducting parallel-plate transmission line stub is used in series with each inductor. The quarter-wave line has an Nb_2O_5 dielectric (ϵ_r = 29) 100 nm thick, formed by anodization. The high dielectric constant, combined with the effect of the magnetic field penetration into the superconductors (λ_L = 85 nm), results in a phase velocity 9.0 times smaller than that of free space. It is thus possible to keep the whole tuning circuit electrically small.

Series array of junctions

In a broadband mixer particular attention must be paid to the possibility of saturation. The dynamic range of an SIS mixer with a series array of junctions is proportional to N^2, where N is the number of junctions in the array [2]-[4]. For this reason the mixers described here use arrays of four junctions.

Configuration of the mixer

The series array of inductively tuned junctions naturally lends itself to incorporation into a coplanar transmission line circuit. The coplanar configuration is desirable for several reasons:

(i) All conductors are on the same side of the substrate, which simplifies fabrication and allows the use of thicker, less fragile substrates.

(ii) Characteristic impedances in the range 50-100 Ω can be obtained on a fused quartz substrate (ϵ_r = 3.8) with reasonable dimensions. This impedance range is suitable for an SIS mixer.

(iii) Because ground currents do not flow in the metal housing which supports the substrate, the circuit is independent of the dimensions of the

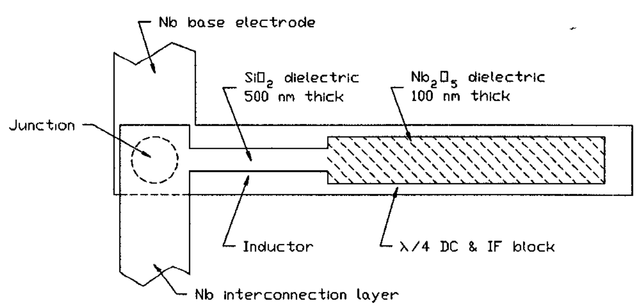

Fig. 1. Inductively tuned SIS junction with quarter-wave DC/IF block.

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housing. (Dimensions must be kept small enough to prevent propagation of any waveguide modes, however.)

(iv) Coplanar lines are easily coupled to other TEM lines (e.g., microstrip or suspended-substrate stripline) which may be used in other parts of a complex integrated subassembly.

The array of inductively tuned SIS junctions is located in a rectangular opening in the ground plane, as shown in Fig. 2. The inductance L_H of the hole is tuned out by capacitor C_H in the figure. To the right of C_H a four-element low-pass filter connects the junctions to an IF amplifier and DC bias supply. An IF and DC ground return is required at the left end of the circuit; this is provided in the RF input circuit and is shown in the next figure.

In the present application the array of junctions is coupled to a WR-10 waveguide via a suspended-substrate stripline and a stripline-to-waveguide transducer. The complete mixer assembly is shown in Fig. 3.

<u>Design using scale models</u>

Several parts of the mixer were designed empirically using large-scale microwave models. The suspended-substrate stripline to waveguide transducer is shown in Fig. 4, and its return loss over the waveguide band is shown in Fig. 5. The transition from suspended-substrate stripline to coplanar transmission line and its return loss are shown in Figs. 6 and 7. The inductance of the hole in the ground-plane which accommodates the array of junctions and their tuners was measured as a function of the length of the hole, as shown in Fig. 8.

SIS JUNCTIONS

For mixer applications, high quality Nb/Al-Al_2O_3/Nb trilayer material may be characterized by a single parameter, the critical current density J_C, which governs the product of the normal resistance R_N and capacitance C_J of a junction. In the present design J_C was chosen to satisfy the following requirements:

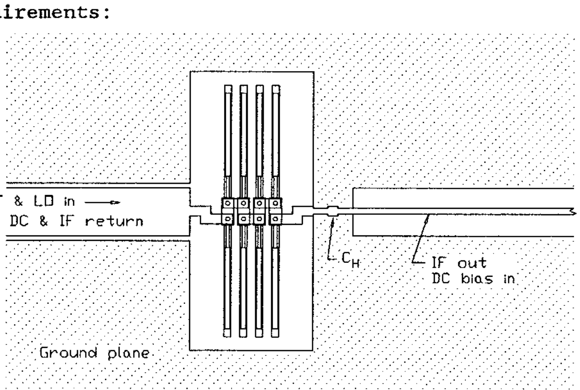

Fig. 2. Array of eight inductively tuned junctions coupled to a coplanar input line (at the left). The inductance L_H of the hole in the ground plane in the vicinity of the array is tuned out by the capacitor C_H.

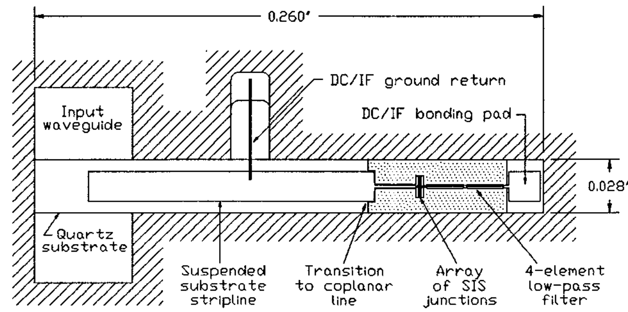

Fig. 3. The complete mixer, showing the waveguide to suspended-substrate stripline transducer, DC and IF ground return stub, and the coplanar mixer circuit.

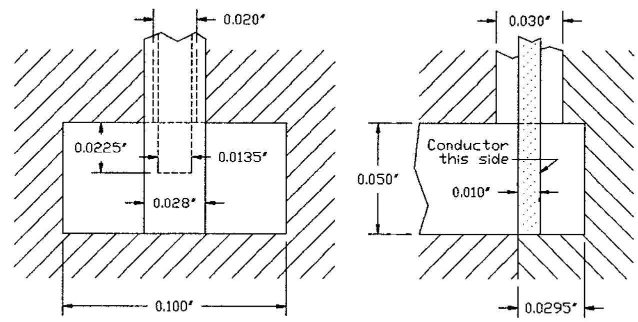

Fig. 4. Suspended-stripline to waveguide transducer.

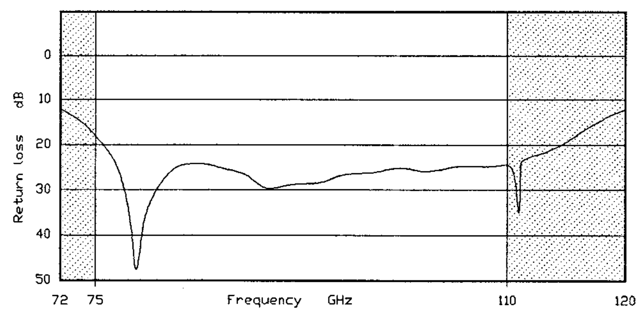

Fig. 5. Return loss of the suspended-stripline to waveguide transducer, measured on a 40 x scale model.

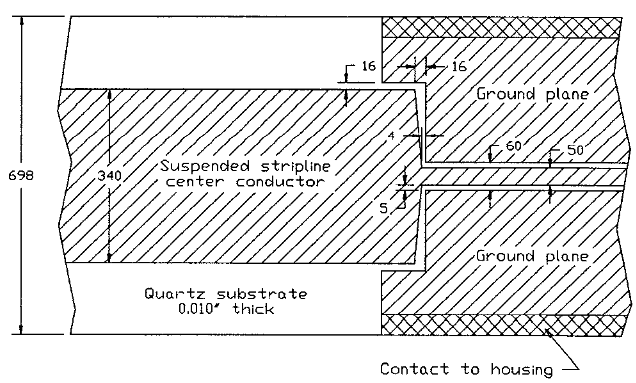

Fig. 6. Suspended-stripline to coplanar line transition. Dimensions in microns.

(i) Low mixer noise temperature.

(ii) Low conversion loss (~ 0 dB). While gain is possible in SIS mixers, substantial gain is usually undesirable because of reduced dynamic range and a greater likelihood of out-of-band instability.

(iii) To achieve wide IF bandwidths, operation into a 50-Ω IF amplifier with no matching transformer is desirable. Note that this does not require the IF output impedance of the mixer to be 50-Ω; SIS mixers can operate well with a high output impedance driving a 50-Ω load.

(iv) A moderately well matched input (VSWR ≤ 2), with the embedding impedance seen by the array of junctions near 50 Ω. This is a practical impedance level for a coplanar transmission line circuit.

(v) The product $\omega R_N C$ should be ~ 5. Here ω is the LO frequency and C is the capacitance of the junction including overlap capacitance between the interconnection layer and base electrode. Based on analysis of published data [5] and simulated mixer results [6], a value of $\omega R_N C$ near 5 appears to give the best SIS mixer performance. This is probably due to the low embedding impedance seen by LO harmonics and harmonic sidebands generated in the junction conductance.

Analysis using Tucker's theory [7,8,2] indicates that these requirements are met with an array of normal resistance $R_{N,A} \approx 100\ \Omega$. For the four-junction array used here, the individual junctions have $R_N = 25\ \Omega$. The specific capacitance of the $Nb/Al\text{-}Al_2O_3/Nb$ trilayer, $C_S = 38\ fF/\mu m^2$, dictates a junction area $A = 8.1\ \mu m^2$ (3.2 μm diameter) including a 4% correction for overlap capacitance. For these trilayer junctions, R_N and the critical current I_C are related by $R_N I_C = 1.8$ mV. The desired critical current density J_C is then 900 A/cm^2.

EXPERIMENTAL RESULTS

The I-V curve of a four-junction array is shown in Fig. 9. From the measured normal resistance of the array (~40 Ω) it is apparent that the critical current density $J_C \approx 2500$ A/cm^2, or about 2.8 times the design goal.

The mixers were installed in the receiver shown schematically in Fig. 10 [9]. The cryogenic HEMT IF amplifier at 1.4 GHz has a noise temperature of ~2 K when operating at 4.2 K. Fig. 11 shows the DSB noise temperature of the whole receiver, measured outside the room temperature vacuum window. Results are also shown for a similar receiver using a mixer with two mechanical tuners [10].

To obtain accurate measurements of the conversion loss and mixer noise temperature, the mixers were installed in the test cryostat described in [10], which had been well calibrated at a LO frequency of 114 GHz. Table I gives the mixer noise temperature, conversion loss, and IF VSWR for two mixers with different tuning inductor lengths. An IF of 1.4 GHz was used with a bandwidth of 50 MHz.

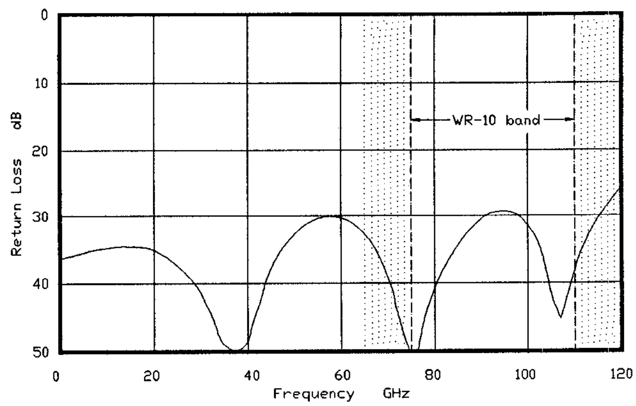

Fig. 7. Return loss of suspended-stripline to coplanar-line transition, measured on a 40 x scale model.

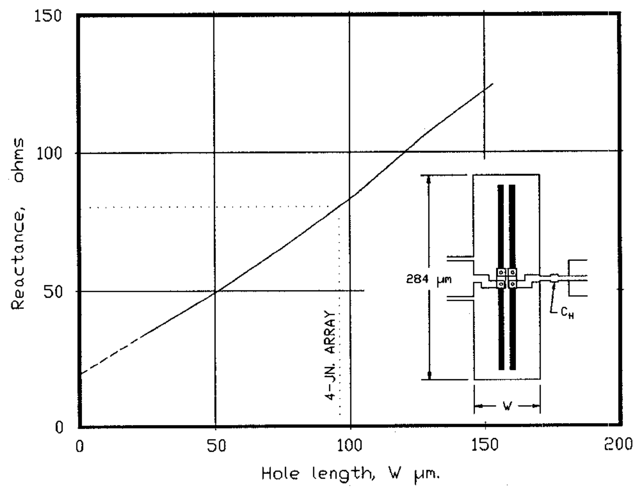

Fig. 8. Inductive reactance of the hole in the ground-plane, measured on a 100 x scale model. For the 4-junction mixers described here, W = 96 microns.

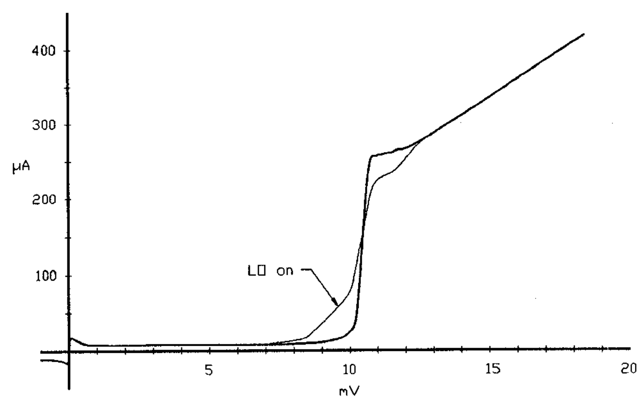

Fig. 9. I-V curve of mixer H3 at 4.2 K, with and without LO power.

TABLE I

MIXER PARAMETERS AT 4.2 K WITH f_{LO} = 114 GHz.

Mixer	L DSB	T_M DSB	IF VSWR
H2	11 dB	27 K	2.2
H3	9 dB	18 K	1.6

DISCUSSION

The mixer noise temperature of 19 K (DSB) at 114 GHz is about three times the expected 6 K, but is acceptably low for practical applications. We have not yet made accurate measurements of T_M at lower frequencies.

The most significant result in Table I is the large conversion loss at 114 GHz – about 10 dB greater than expected. We have not made accurate conversion loss measurements at lower frequencies, but surmise that the pronounced improvement in receiver noise temperature towards the lower end of the band, evident in Fig. 11 for mixer H3, must be a result of lower conversion loss. Measurement of the *ratio* of conversion loss in the upper and lower sidebands indicates that they are equal within 1 dB (the measurement accuracy) from 75-114 GHz.

The effects of the high value of J_C have been calculated theoretically. For $J_C = 2500\ A/cm^2$ it is expected that a conversion *gain* of 5-10 dB (DSB) would be observed, with $T_M \approx 12$ K (DSB) and a large positive or negative output impedance (i.e., G_{out} near zero). In our experiments we have not observed large positive or negative output impedances in these mixers.

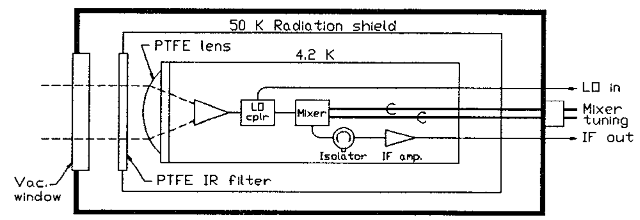

Fig. 10. Schematic diagram of cryostat used for receiver measurements.

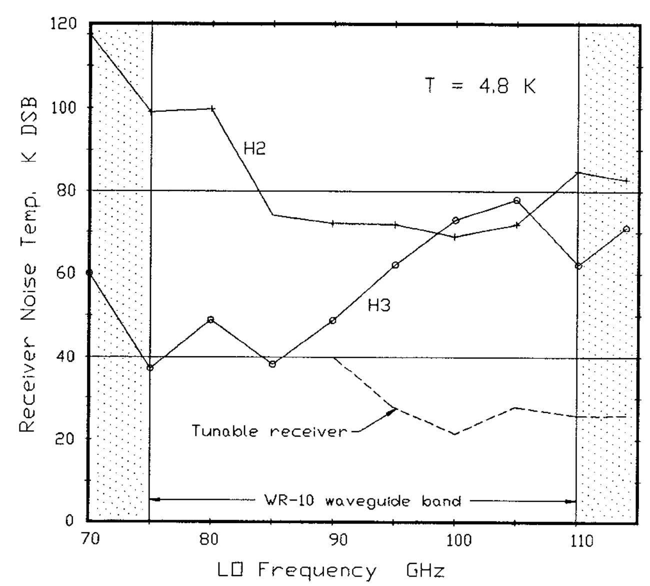

Fig. 11. DSB noise temperature of the overall receiver operating at 4.8 K, for two inductor lengths. Results for tunable receiver shown for comparison.

SYNOPSIS

We have demonstrated a fully integrated, low-noise, SIS mixer for 75-110 GHz with no adjustable tuners. The unexpectedly large conversion loss of the mixers has not yet been explained. Simple coplanar topology is used. This eliminates the need for registering patterns on opposite sides of a wafer, and allows the use of a conveniently thick substrate (0.010") in the mixer. The design is readily integrable with other components, such as planar antennas or future superconducting IF processors. The design should be useful up to 300 GHz, and possibly to 600 GHz, with appropriate frequency scaling.

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