SOME RECENT DEVELOPMENTS IN THE DESIGN OF SIS MIXERS

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ABSTRACT

This paper describes SIS mixers in use or under development at NRAO, and introduces a new design procedure for SIS mixers.

By using broadband waveguide-to-stripline transducers, it is possible to design SIS mixers which do not require reduced-height waveguide. At the shorter millimeter wavelengths this greatly simplifies mixer fabrication and allows the use of non-contacting waveguide tuners.

The use of superconducting circuit elements integrated with the junction (or array of junctions) to tune out the usually large junction capacitance has made possible a tunerless mixer which covers a full waveguide band.

The new design procedure for SIS mixers aims at meeting certain practical design constraints on noise temperature, conversion loss, input match, and load impedance. It is found that the ratio of normal resistance to source resistance, R_N/R_S, should have a 1/f dependence for mixers in the quantum-limited regime. The $\omega R_N C = 4$ rule is modified to $\omega R_N C = 4(100/f(\text{GHz}))$, which requires a critical current density $J_C \propto f^2$. The implications of this design procedure are examined for the case of $Nb/Al\text{-}Al_2O_3/Nb$ junctions, and design curves are given for R_N, J_C, and junction size as functions of frequency.

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1. INTRODUCTION

Because of their high sensitivity, reasonable bandwidth, and small LO power requirements, SIS receivers are now widely used for millimeter-wave radio astronomy. To date about ten observatories worldwide are routinely using SIS receivers from 43 to 360 GHz, and in the near future this number will increase to at least fifteen. Despite their widespread use, many SIS receivers are little or no more sensitive than the best cryogenic Schottky diode mixer receivers, and few have approached the ultimate sensitivity limit imposed by the uncertainty principle.

Fig. 1 shows the noise temperatures reported for SIS receivers up to 400 GHz and, for comparison, the present limit for Schottky mixer receivers.

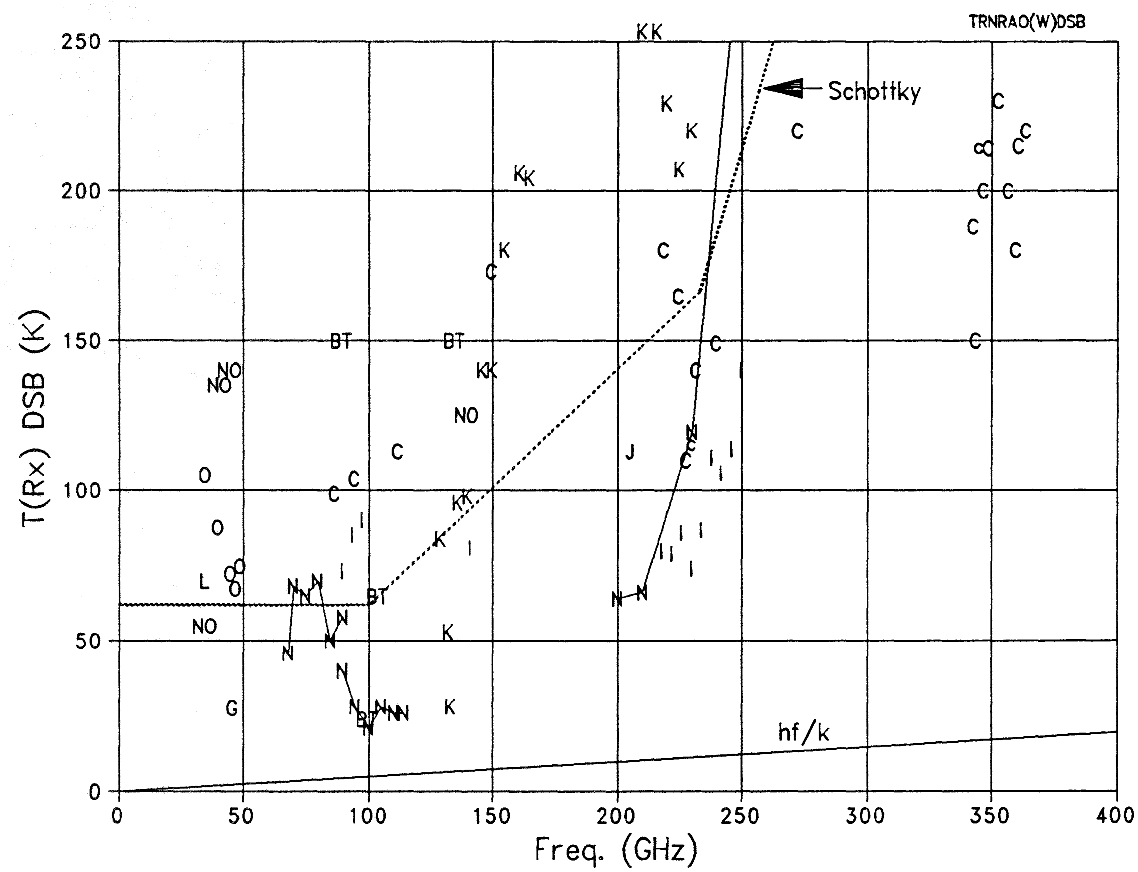


Fig. 1. Double sideband noise temperatures of the better SIS receivers in the frequency range 0-400 GHz. The following coding is used: BT=Bell Labs, C=CalTech, c=CalTech (quasi-optical), G=GISS/Princeton, I=IRAM, J=JPL, K=U. of Koln, L=LETI, N=NRAO, NO=Nobeyama. The performance of the best Schottky receivers is shown by the dotted line. Receivers developed at NRAO are indicated by a solid line, as is the photon noise temperature hf/k.

We believe there are two main reasons that SIS receivers have been slow to develop their full potential: the lack of high-quality SIS junctions with appropriate properties, and the difficulty of tuning out the usually large junction capacitance. In the following sections we describe the approach we have taken to designing SIS mixers at NRAO.

2. SOME NRAO SIS MIXER DESIGNS

2.1 The GISS Type-D, 90-116 GHz mixer

The GISS Type-D mixer [1,2] is shown in Fig. 2. In this mount a series array of SIS junctions is suspended across a reduced-height waveguide. Two waveguide tuners allow the embedding admittance seen by the junctions to be set anywhere in the complex plane except in the forbidden region indicated in Fig. 2(c). This design has been successful using SIS junctions with and without integrated circuits to tune out the junction capacitance [3]. Without integrated tuning circuits, the mixer can be tuned

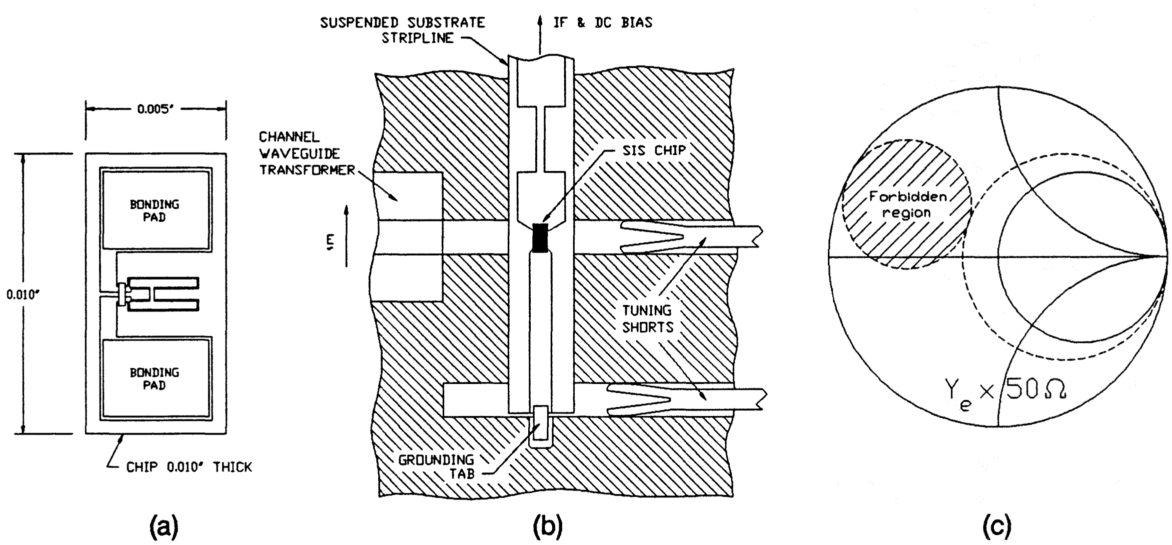


Fig. 2. The GISS Type-D, 90-116 GHz, SIS mixer uses a 0.005" x 0.010" chip (a) with a series array of 2 or 4 junctions, mounted across a 1/4-height waveguide on a quartz suspended-substrate stripline, as shown in (b). The mixer block is split along the middle of the broad walls of the waveguides. The stripline crosses a second waveguide containing an adjustable tuner which provides a variable reactance in series with the junctions. The embedding admittance can be adjusted to any value outside the forbidden region indicated in (c). A channel waveguide transformer [4] is used to reduce the waveguide height from 0.050" to 0.0125" in the vicinity of the junctions. The suspended substrate is fused quartz 0.023" wide x 0.003" thick. The SIS chip shown in (a) has a two-junction array with the integrated tuning circuit described in [2].

to obtain good performance and 20 dB image rejection. While this mixer can be scaled for use at lower frequencies, scaling to higher frequencies is difficult because of the small size of the 1/4-height waveguide and the poor quality of adjustable waveguide short-circuits in such small waveguides.

2.2 The NRAO-401, 140-260 GHz mixer

The NRAO-401 mixer for the WR-4 waveguide band was designed to overcome the limitations on scaling the GISS Type-D mixer to higher

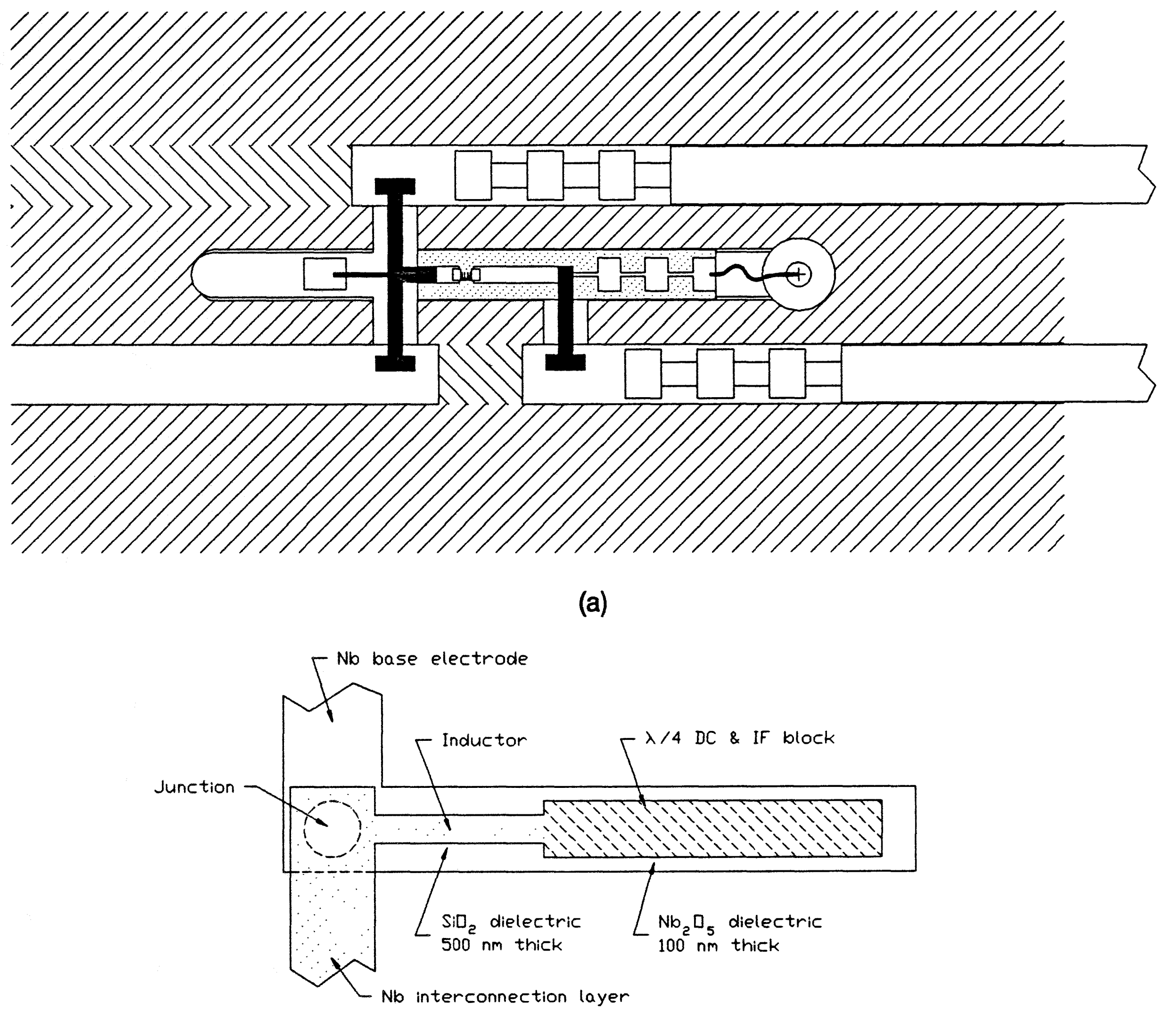


Fig. 3. NRAO-401, 140-260 GHz mixer. (a) The SIS junctions are on a 0.005" x 0.010" quartz chip which is soldered face-down on the larger fused quartz substrate (shown dotted) and then ground to a thickness of ~0.0005". The free-standing striplines (shown solid) are photo-fabricated from 0.001" copper and soldered to the main substrate. The main substrate is fused quartz 0.0025" thick x 0.018" wide. The waveguide height is 0.0215". The mixer uses a series array of individually tuned junctions [3], as shown in (b). An inductive tuning circuit with a DC/IF block tunes out the capacitance of each junction.

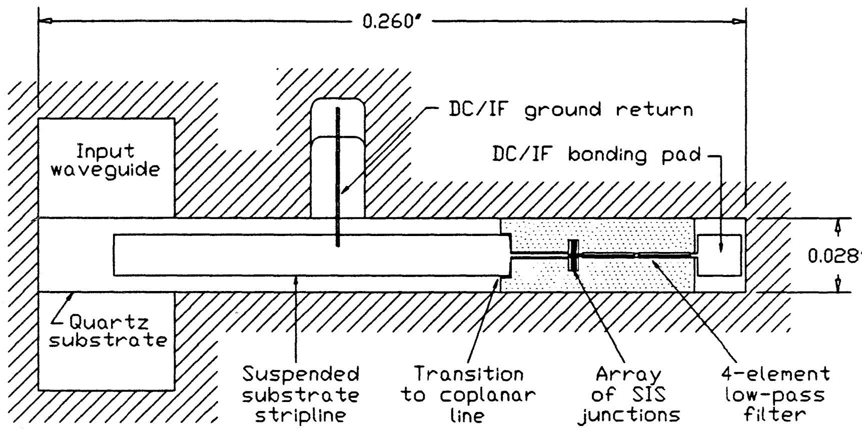
frequencies. Two adjustable tuners are again used, but these are in full-height waveguide in which non-contacting short circuits are practical [5]. Power is coupled from the input waveguide to the SIS junctions via a broadband transition to a 50-Ω self-supporting copper stripline, followed by a suspended-substrate stripline, as shown in Fig. 3(a). The two tuners are likewise coupled to the junctions and provide series and parallel tuning elements. At the left end of the diagram, a $\lambda/4$ stub to ground provides a DC and IF return. This mixer uses an array of individually tuned junctions as shown in Fig. 3(b) [3]. The mixer block is split along the middle of the broad walls of the waveguides. Fabrication of the block is relatively straightforward. The two halves are machined simultaneously: two long waveguide slots and the substrate slot are milled right across both halves, and the waveguides are later plugged as indicated by the reverse hatching in the figure.

2.3 A tunerless mixer for 75-110 GHz

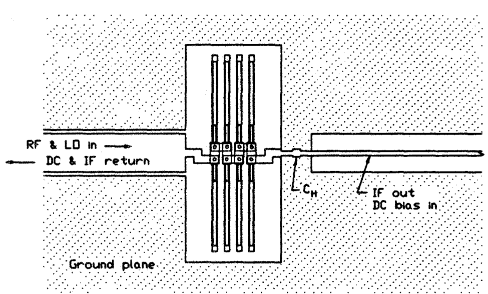
The reduced size of a fully integrated SIS mixer circuit results in greatly reduced parasitic reactances compared with the mixers described above. It then becomes feasible to design a mixer with no adjustable tuners which covers a full waveguide band. The mixer shown in Fig. 4(a) [6] operates in the WR-10 band (75-110 GHz). The heart of the mixer, shown in Fig. 4(b), is a coplanar transmission line connected to a series array of individually tuned junctions (see Fig. 3(b)). The coplanar line makes a broadband transition to suspended-substrate stripline, which then couples into a waveguide via a broadband probe transducer.

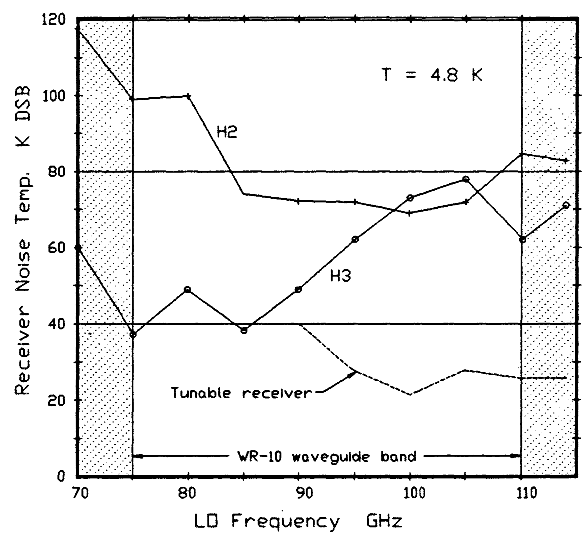
In the form shown here, the mixer is coupled to an input waveguide, but the same basic coplanar design (Fig. 4(b)) is equally suitable for operation in more complex, fully planar systems, e.g., in a planar quasi-optical receiver with a slot, dipole, or spiral antenna.

The noise temperature of two receivers using mixers of this type is shown in Fig. 4(c).



(a)





(b) (c)

Fig. 4. The tunerless mixer for 75-110 GHz is on a 0.010" thick x 0.028" wide quartz substrate coupled to the WR-10 waveguide shown at the left in (a). Power from the waveguide is coupled to the SIS junctions via a broadband probe transducer to a suspended-substrate stripline, followed by a broadband transition to coplanar transmission line. The junctions are located in a hole in the ground plane metalization as shown in (b). The inductance of this hole is tuned out by the capacitance C_H. Contact between the edges of the ground plane and the shoulders of the substrate channel is made by gold wire gaskets. The SIS array has individually tuned junctions [3] as shown in Fig. 3(b). The noise temperature of a receiver using mixers with two different tuners is shown in (c), and the noise temperature of a tunable receiver using a GISS type-D mixer is shown for comparison.

3. A DESIGN PROCEDURE FOR SIS MIXERS

3.1 Design requirements

For most applications the following properties are desirable in SIS mixers:

(i) Low mixer noise temperature.

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

(iii) A moderately well matched input (VSWR $\leq$ 2). A source impedance near 50 Ω is practical in many types of mixer mount.

(iv) 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.

3.2 RF source impedance

Using Tucker's theory in its three frequency approximation [7-9], we have investigated the behavior of SIS mixers as a function of LO frequency and amplitude for various source and load impedances. We assumed a low IF, and a broadband embedding circuit which tunes out the junction capacitance in the upper and lower sidebands. The bias point was taken as the middle of the first photon step below the gap voltage. Two types of junction were considered, Nb/Al-Al_2O_3/Nb trilayer junctions and Nb/oxide/PbInAu edge-junctions. The calculations were based on the I-V curves, shown in Fig. 5, of mixers which had given good results in the laboratory. (These I-V curves are actually for two- and four-junction series arrays; however, as series arrays are theoretically equivalent to single junctions, this is immaterial [9,10].)

From these calculations we have found that the design requirements above can normally be satisfied by the appropriate choice of the ratio (junction normal resistance)/(RF source resistance), R_N/R_S. Fig. 6 shows the dependence of the optimum value of R_N/R_S on frequency.

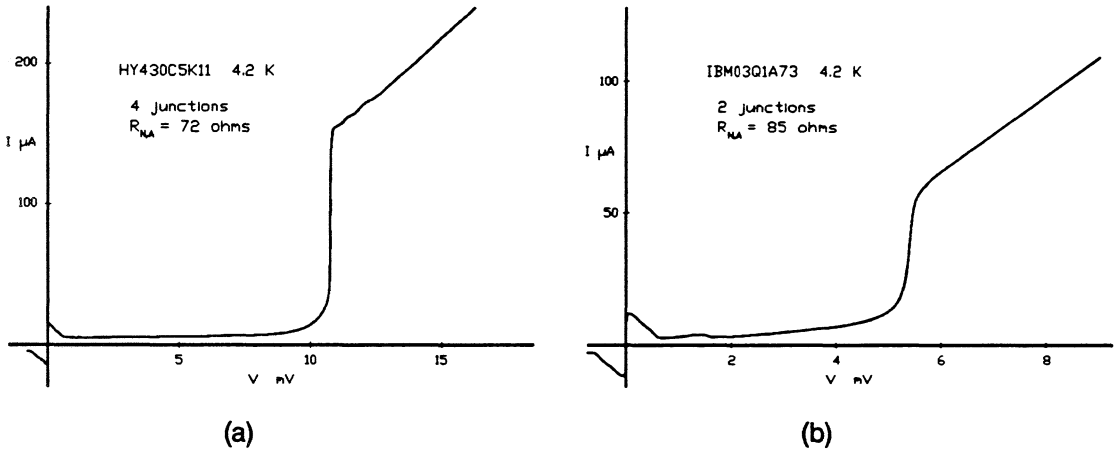


Fig. 5. I-V curves of (a) a four-junction array of Hypres Nb/Al-Al_2O_3/Nb junctions, and (b) a two-junction array of IBM Nb/oxide/PbInAu edge junctions.

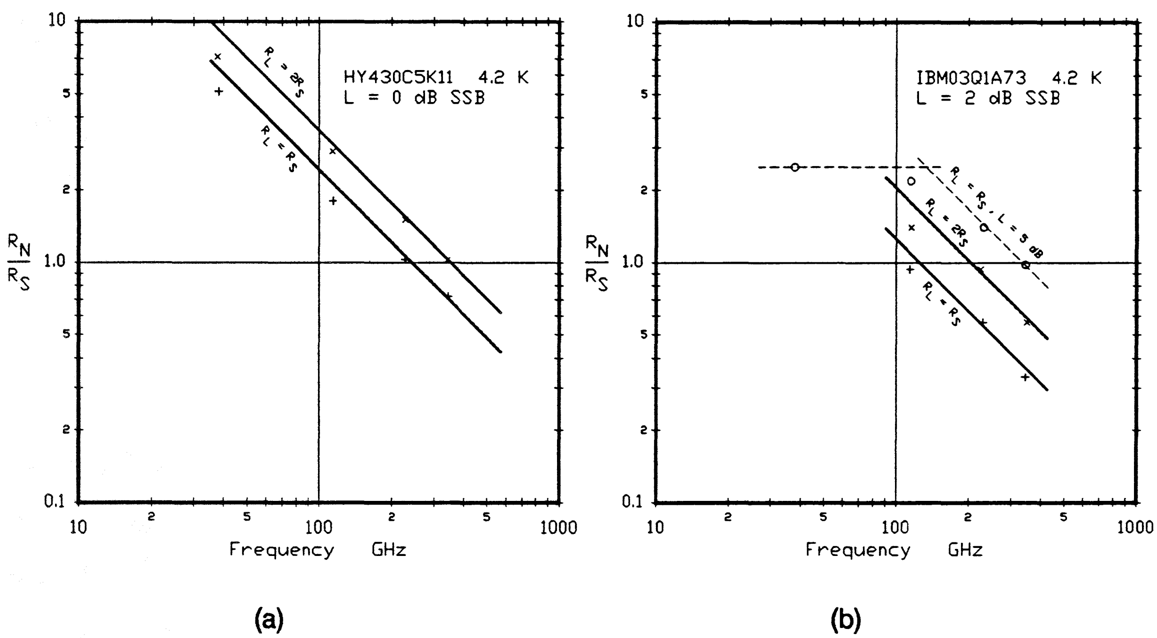


Fig. 6. Optimum ratio of (array) normal resistance to source resistance, R_N/R_S, as a function of frequency. With the indicated R_N/R_S, the mixer can operate with low noise, gain near unity, and a reasonably well matched input. Graph (a) is for the Nb/Al-Al_2O_3/Nb junctions of Fig. 5(a) with IF load impedance $R_L = R_S$ and $2R_S$. For this case, the relatively sharp I-V curve allows mixer operation with strong quantum characteristics (e.g., L = 0 dB SSB) well below 100 GHz. Graph (b) is for the Nb/oxide/PbInAu edge junctions of Fig. 5(b) which have a much softer I-V curve. In this case it was not possible to obtain unity conversion loss at the lowest frequencies, so the criterion L = 2 dB was used in plotting the lower two curves which are for IF load impedances $R_L = R_S$ and $2R_S$. The upper curve is for L = 5 dB with $R_L = R_S$, and is included to show the clear break between the low-frequency region, where the mixer is predominantly classical and R_N/R_S is independent of frequency, and the high-frequency region, in which quantum effects are dominant and $R_N/R_S \propto 1/f$.

3.3 A modification of the $\omega R_N C = 4$ rule

A parameter widely used in characterizing SIS mixers is the $\omega R_N C$ product. Here ω is the LO frequency, R_N is the normal-state junction resistance, and C is the capacitance of the junction including overlap capacitance between the interconnection layer and base electrode. Based on analysis of published data [10] and simulated mixer results [11], mostly for mixers near 100 GHz, a value of $\omega R_N C$ near 4 appears to give the best SIS mixer performance. This is believed to be due to the low embedding impedance presented by C to LO harmonics and harmonic sidebands generated in the junction conductance. There is no reason to assume this optimum value of $\omega R_N C$ is not frequency dependent.

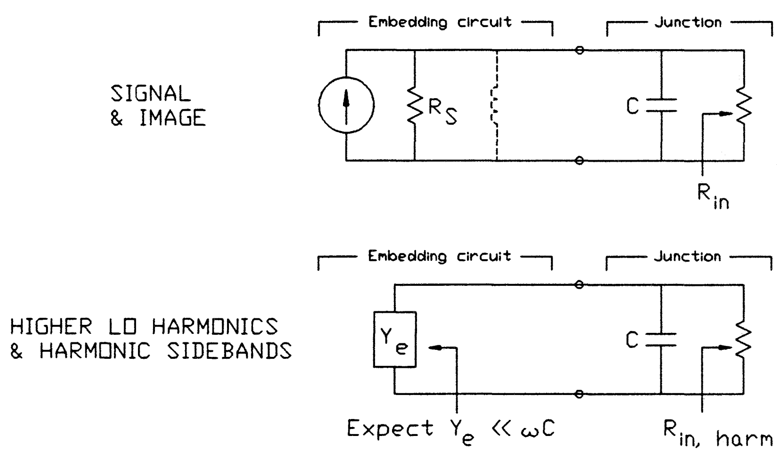


Fig. 7. RF equivalent circuit of an operating SIS mixer at the signal and image frequencies ($f_{LO} \pm f_{IF}$) (upper diagram), and at the LO harmonic (nf_{LO}) and harmonic sideband ($nf_{LO} \pm f_{IF}$) frequencies (lower diagram). In a practical circuit, it is almost certain that the junction capacitance C will dominate the embedding admittance at the LO harmonic and harmonic sideband frequencies.

Consideration of the RF circuit of an operating SIS mixer, as in Fig. 7, suggests that the quantity which governs the effect of the capacitance C at the LO harmonics and harmonic sideband frequencies is actually $R_{in,harm}$, rather than the DC normal resistance R_N. It should then be $\omega R_{in,harm} C$ rather than $\omega R_N C$ which is used as a frequency-independent parameter in designing mixers. $R_{in,harm}$ is related to the signal-frequency input impedance R_{in}, and in the quantum-limited regime, with the mixer designed to meet the above design requirements, we expect $R_{in,harm}/R_{in}$ to be relatively independent of frequency. Hence, $\omega R_{in}C$ can be used as a frequency-independent parameter. If the input of the mixer is matched, $R_S = R_{in}$, so $\omega R_S C$ also becomes frequency independent. It is clear from Fig. 6 that in the quantum-limited regime, the optimum R_N/R_S is inversely proportional to frequency. It follows that the optimum $\omega R_N C$ is also inversely proportional to frequency, and hence the $\omega R_N C = 4$ rule for mixers near 100 GHz should be modified to include the frequency dependence:

$$\omega R_N C = 4 \, \frac{100}{f(\text{GHz})} \quad . \tag{1}$$

3.4 Required junction area vs. frequency

For a particular type of junction – e.g., Nb/Al-Al_2O_3/Nb trilayer or Nb/oxide/PbInAu edge junctions – the specific capacitance C_s is almost independent of the critical current density J_C, and will be taken as constant. Given the RF source resistance R_S, the normal resistance R_N is obtained from Fig. 6. The junction capacitance C is then deduced from eq. (1). If stray (overlap) capacitance can be ignored, then for a single-junction mixer, the desired junction area is

$$A = \frac{400}{f(\text{GHz})} \; \frac{1}{\omega R_N C_s} \quad . \tag{2}$$

In the quantum-limited regime, with $R_N \propto 1/f$ (at constant source resistance R_S), the junction area A is therefore inversely proportional to frequency. This is also obvious from the constraint, discussed in the previous section, that $\omega R_S C$ be independent of frequency.

For a mixer with a series array of N junctions, R_N in (2) is replaced by the normal resistance of the whole array $R_{N,a}$. Then for the individual junctions $R_N = R_{N,a}/N$, and the area of each junction is

$$A = \frac{400}{f(\text{GHz})} \; \frac{N}{\omega R_{N,a} C_s} \quad . \tag{3}$$

3.5 Required J_C vs. frequency

Theoretically, the product $R_N I_C$ for a tunnel junction is a function only of the superconducting energy gap $\Delta(T)$. At 4.2 K, for Nb/Al-Al_2O_3/Nb trilayer junctions $R_N I_C \simeq 1.8$ mV, and for Nb/oxide/PbInAu edge junctions $R_N I_C \simeq 1.6$ mV. Given the junction area and normal resistance, the critical current density is

$$J_C = \frac{(R_N I_C)}{R_N A} \tag{4}$$

Under the design requirements discussed above, R_N and A are each inversely proportional to frequency for quantum-limited mixers, so $J_C \propto f^2$.

3.6 Design of Nb/Al-Al_2O_3/Nb mixers

As an example of the above design procedure, consider the design of Nb/Al-Al_2O_3/Nb trilayer SIS mixers for various frequencies. The I-V curve of Fig. 5(a) is assumed, with source and load impedances of 50 Ω, a specific capacitance $C_s = 45$ fF/μm^2 [12] and $R_N I_C = 1.8$ mV. The calculations are for a single junction.

- (i) From Fig. 6(a), $R_N/R_S = 2.5 \times 100/f(\mathrm{GHz})$, so $R_N = 12500/f(\mathrm{GHz})$.
- (ii) From eq.(2), the junction area $A = 113/f(\mathrm{GHz})$ μm^2.
- (iii) From eq.(4), The critical current density $J_C = 0.13\, f^2(\mathrm{GHz})$ A/cm^2.

These results are shown graphically as functions of frequency in Figures 8 and 9.

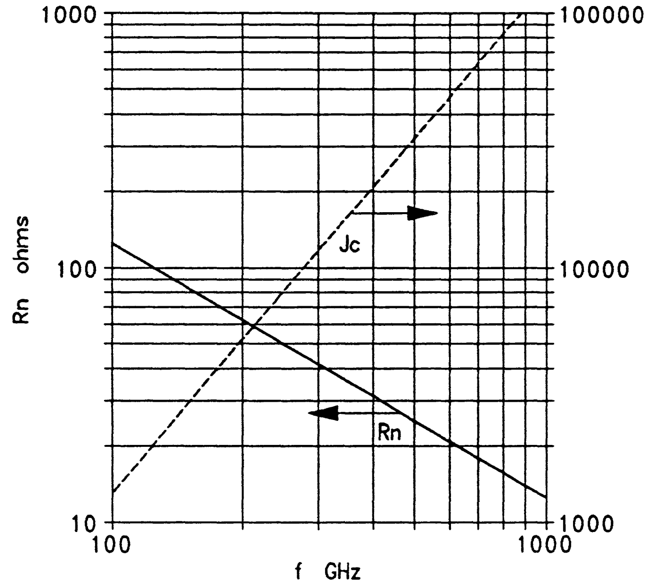


Fig. 8. Required normal resistance R_N and critical current density J_C (A/cm^2) for a mixer using a Nb/Al-Al_2O_3/Nb junction with 50-Ω source and load impedances. When a series array of junctions is used, R_N is the normal resistance of the array ($R_{N,a}$).

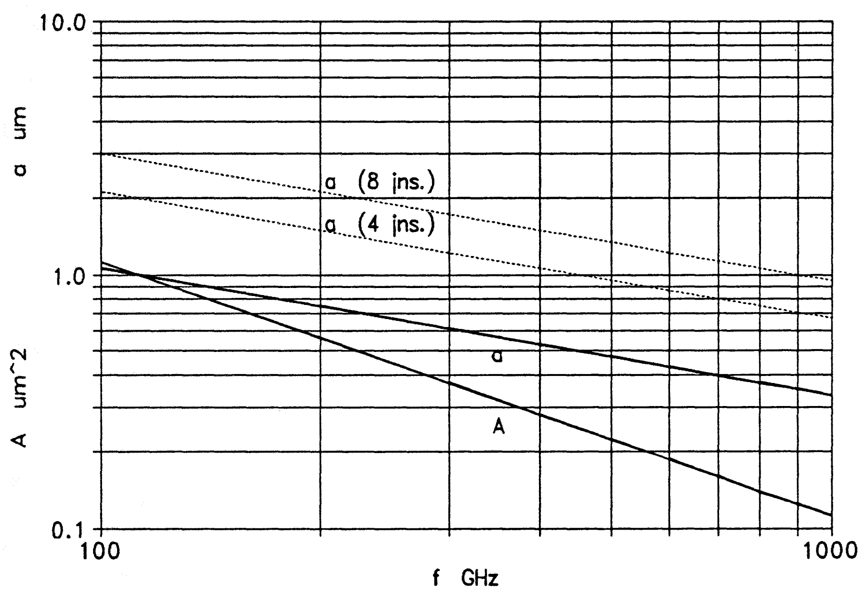


Fig. 9. Required junction area A (μm^2) and side a (μm) (assuming square junctions) for a mixer using a single Nb/Al-Al_2O_3/Nb junction with 50-Ω source and load impedances. The dashed curves give the size of junctions (a μm) required for series arrays of four and eight junctions.

4. SUMMARY

By using broadband waveguide-to-stripline transducers, it is possible to design SIS mixers which do not require reduced-height waveguide. At the shorter millimeter wavelengths this greatly simplifies mixer fabrication and allows the use of non-contacting waveguide tuners.

The use of superconducting circuit elements integrated with the junction (or array of junctions) to tune out the junction capacitance has made possible a tunerless mixer which covers a full waveguide band.

A new approach to SIS mixer design allows the mixer to have low noise, gain near unity, and a reasonably well matched input. The ratio of normal resistance to source resistance, R_N/R_S, is then inversely proportional to frequency. The $\omega R_N C = 4$ rule is modified to $\omega R_N C = 4(100/f(\mathrm{GHz}))$, which requires a critical current density $J_C \propto f^2$.

The implications of this design procedure are examined for the case of $Nb/Al\text{-}Al_2O_3/Nb$ junctions, and design curves are given for R_N, J_C, and junction size as functions of frequency.

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