SUBMILLIMETER WAVE DETECTION WITH SUPERCONDUCTING TUNNEL DIODES

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ABSTRACT

Superconductor-Insulator-Superconductor (SIS) diodes are the detector elements in the most sensitive heterodyne receivers available from 100 to 500 GHz. SIS mixers are the front end of radio astronomical systems around the world. SIS mixer technology is being extended to 1 THz and higher frequencies for eventual use on spaceborne astronomical experiments.

Here is a short review of submillimeter SIS mixers. The role of impedance matching in the proper design of an SIS mixer is described. A variety of methods for achieving good impedance match at submillimeter frequencies are presented. The experimental state of the submillimeter SIS mixer art is described and summarized.

1. INTRODUCTION

Twelve years ago, the first descriptions of mixing on a superconducting tunnel diode called a Superconductor-Insulator-Superconductor (SIS) were published [1, 2] . At about the same time, a comprehensive theoretical investigation of the SIS made clear that SIS's respond to photons at millimeter and submillimeter wavelengths [3]. The SIS has become the instrument of choice for millimeter spectroscopic radio astronomy, finding use on radio telescopes around the world [4-13]. Since the discovery of the SIS mixer, the technology for fabricating SIS circuits has improved immensely so that nearly ideal niobium devices with sub-micron feature sizes can be fabricated [14-20]. Recently, the high performance of SIS mixers has been extended to submillimeter wavelength radio astronomy [8, 21-23, 20, 24].

This paper is a shortened version of a review published elsewhere [25]. The full review includes an in-depth introduction to the field of SIS mixing. An excellent and comprehensive earlier review of both theory and experiment is that of Tucker and Feldman [26]. Reviews of the state of the art of SIS mixers have appeared regularly [27-30]. Other reviews include both SIS mixers and competing receiver technologies used in radio astronomy [31, 32].

2. RF ADMITTANCE OF THE SIS

The SIS mixer has two important rf input admittances. The first one is Y_{LO}, the admittance the SIS presents to the LO. The second is Y_{IN}, the admittance the SIS mixer presents at the signal frequency. Because the signal power must always be much less than the absorbed LO power for a mixer to avoid saturation, it is useful to think of Y_{LO} as the "large signal admittance" of the SIS, and Y_{IN} as the "small signal admittance."

For a submillimeter SIS mixer, Y_{LO} is generally quite close to G_N, the dc normal state admittance of the SIS. Y_{LO} is nearly constant over the range of useful dc and LO biasing conditions. Y_{LO} is completely independent of the signal, image, LO, and harmonic source admittances to which the SIS is coupled. In fact, Y_{LO} is the admittance presented by the SIS seen as a passive absorber of radiation.

Y_{IN}, on the other hand, is a highly variable quantity. It does change with all of the parameters mentioned above. It is possible for Y_{IN} to have a negative real part, while Y_{LO} must always have a positive real part. For this reason, Y_{IN} must be interpreted as the input admittance of the SIS viewed as an active device powered by the LO.

2.1. *SIS Parasitic Capacitance*

In submillimeter SIS mixers, a dominant part of the SIS's rf admittance is due to its parasitic capacitance. The capacitance per unit area of the SIS junctions used in submillimeter mixers is nearly a constant depending only on the materials from which the junctions are made. Numbers commonly used in design are 50 $fF/(\mu m)^2$ for lead alloy SIS's, and 50 to 70 $fF/(\mu m)^2$ for niobium SIS's with aluminum-oxide insulating layers.

Many mixer designers aim to minimize the SIS capacitance. In fact, many of the best SIS mixers have been built with low capacitance junctions. The lowest SIS receiver noise temperature at 230 GHz are achieved with 0.25 $(\mu m)^2$ Nb junctions with $C = 1.7 \times G_N/2\pi f$ [13]. Open-structure SIS mixers have work fairly well at their low frequency ends where $C < 1.0 \times G_N/2\pi f$ [8, 33].

However, there is some evidence that $C \approx 3 \times G_N/2\pi f$ provides more benefit than harm in a well designed SIS mixer. The reasons for this, and the value of the optimum capacitance are discussed in these references [11, 34]. The larger capacitance seems especially important when series arrays of SIS's are used [35].

Whether or not a non-zero capacitance is helpful becomes a less important question as the operation frequency of SIS mixers is raised. All suggestions of a non-zero capacitance still have that optimum falling as f^{-1} or f^{-2}. As f is raised it becomes increasingly difficult to fabricate SIS's with C less than any of the proposed optimum values.

2.2. *Optimum Signal Source Admittance: Match to Y_{LO}*

The signal appears to come from a source admittance Y_S. The value of Y_S is one of the major design available to an SIS mixer designer. For submillimeter SIS mixers, the proper choice is $Y_S = Y^*_{LO}$. This choice of Y_S minimizes the SIS mixer noise temperature. This result is predicted from photodiode mixer theory [25], and also by detailed Tucker theory calculations [36].

It is paradoxical that it is not the actual small signal admittance Y_{IN} to which the mixer structure must supply a match, but the large signal LO admittance, Y_{LO}. In fact, a choice of $Y_S = Y^*_{IN}$ will maximize the SIS mixer's gain instead of its noise. Because IF amplifiers have very low noise levels, it is much more important to minimize mixer noise than to maximize mixer gain in submillimeter SIS mixers.

3. IMPEDANCE MATCHING TECHNIQUES

There are two tasks which must be accomplished to match the signal source admittance Y_S to the SIS's input admittance Y_{LO}. First, the values of Y_{LO} typical of SIS's are much larger than the source admittances presented by most antennas and waveguide structures. Second, the parasitic capacitance of the SIS must be tuned out. These two tasks can be accomplished in a few different ways. In some cases, a single tuning structure can do both of these things simultaneously.

3.1. *Integrated tuning*

It is a relatively simple matter to integrate tuning structures with the SIS diode in its photolithographic stage of fabrication. There are at least two layers of low loss superconductor required in SIS fabrication, which allows for various "two-wire" tuning elements. With the addition of a thick (around 2,000 Å) insulating layer, stripline tuning structures can be fabricated.

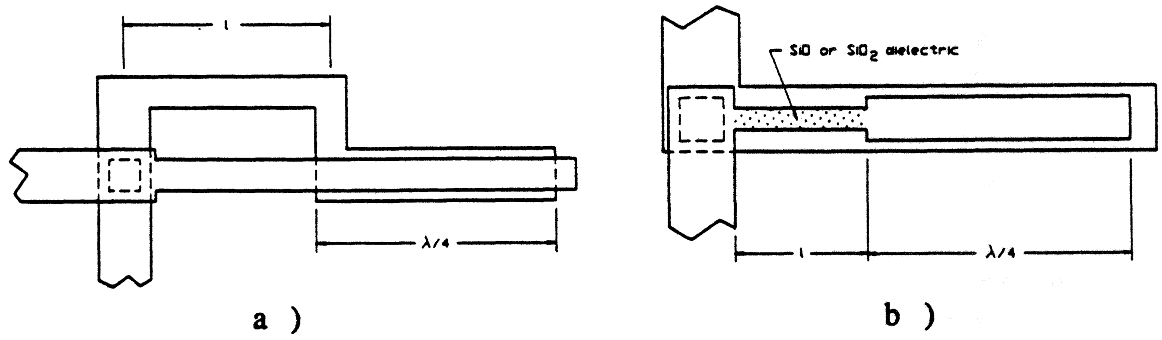

Figure 1 [38]. Two tuning structures integrated with SIS junctions. a) The sickle-shaped piece is the bottom layer of superconductor, the straight piece the top. Where the two layers overlap, they are actually separated by a thick (~2,000 Å) layer of insulator, except in the dashed square, where they come much closer to form the SIS. b) A tuning structure based entirely on microstrip.

Direct measurements of the efficacy of tuning elements in the 100-500 GHz range have been made using Fourier Transform Spectrometer (FTS) measurements [37].

The two tuning structures shown in fig. 1 are compact and simple designs proposed by Kerr, Pan, and Feldman [38]. Their primary role is to provide an inductance at the SIS which tunes out its parasitic capacitance. The structure shown in b) is particularly appropriate for higher rf frequencies. In both a) and b) structures are shown which are $\lambda/4$ in length. Here, λ refers to the wavelength associated with rf radiation propagating along the integrated tuning structure. The structures labeled with length $\lambda/4$ are designed to present a short circuit to the rf at their left ends, but are open circuited at dc and f_{IF}. In a), the tuning structure shown to be *l* long is essentially a single-turn inductor. In b), the tuning structure shown to be *l* long is a short length of high impedance microstrip. Since it is rf-shorted at one end, it presents an inductive susceptance across the SIS. The reactances associated with these structures are very small at the IF and so have no effect on the IF or dc properties of the mixer.

Using SIS circuits designed with integrated tuning, it is possible to build SIS mixers with no mechanical tuning which have excellent responsivity over an entire waveguide band at millimeter wavelengths [11, 39]. These two mixers are quite different in their design, both should be reviewed for a good appreciation of the range of integrated tuning circuitry which is possible.

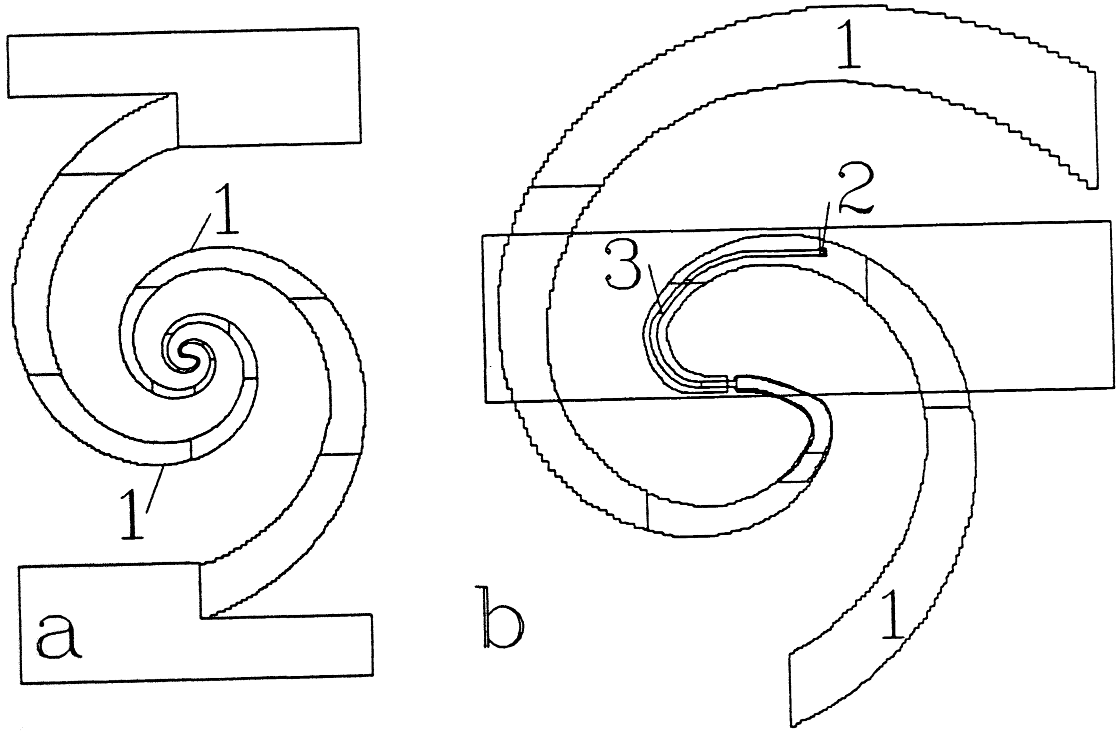

Figure 2 [40]. A spiral antenna SIS mixer with transmission line tuning. a) The radiation coupling structure is a 3.4 mm diameter spiral antenna. b) Instead of placing the SIS at the central leads of the spiral (1), a microstripline (3) is formed and the SIS (2) is placed at its end.

3.2. *Microstrip transmission line transformers*

The inductive structures shown above address only the problem of tuning out SIS parasitic capacitance. Using microstrip transmission lines, it is possible to tune out the SIS's capacitance and to lower Y_{LO} to a more convenient value.

The simplest circuit which does this is shown in fig. 2. The large-scale structure shown in a) is a spiral dipole antenna. Radiation coupled by this antenna to the antenna leads at its center has a source admittance of about $(114\ \Omega)^{-1}$. Rather than placing the SIS at the center of the antenna, the SIS is placed at the end of a microstrip transmission line as shown in b). One of the poles of the antenna is used as the ground plane for this transmission line. The transmission line has a fairly low impedance and a length chosen so that the SIS's high value of Y_{LO} is transformed down to about $(114\ \Omega)^{-1}$ where it is connected to the center of the antenna. In fact, the transmission line transformer is a little longer than a standard quarter-wave transformer so that it also tunes out the SIS's parasitic capacitance.

This simple technique can be extended in useful ways. The junction need not be placed at the end of the transmission line structure [41]. A symmetric structure with junctions and transmission lines on both antenna leads adds flexibility to design and will avoid mismatch due to the transition from a balanced mode on the antenna to an unbalanced mode on the microstrip [41]. A multi-step (Chebyshev) transformer can be used for excellent broadband performance [42]. The transformation to low impedance junctions improves the dynamic range of the mixer [41]. A tapered transmission line transformer can provide a broadband match [23].

4. SIS MIXER RESULTS

SIS mixers of some variety have been built. Niobium technology is the best current choice for submillimeter SIS's. Both waveguide and quasioptical coupling structures are useful at these high frequencies. Integrated tuning structures of increasing complexity are being used to improve mixer performance.

4.1. SIS Junction Fabrication

Many of the best SIS mixers use lead alloy SIS junctions. However, niobium and niobium alloy junctions have such great advantages that even the fabricators of lead alloy SIS's are developing niobium technology. Niobium junctions have been fabricated and used in high performance SIS mixers [15, 18, 19, 43, 13, 23]. Niobium-nitride alloy SIS's [17, 44] are interesting as they will operate at higher temperatures, and possibly higher frequencies than pure niobium SIS's.

4.2. Radiation coupling structures

A sensitive SIS mixer requires an SIS junction which is well coupled to its input radiation. The coupling structure chosen effects this in two important ways. 1) The coupling structure determines Y_S, the source admittance from which the radiation appears to come. 2) The coupling structure determines the beam pattern of the SIS mixer. A good beam pattern is essential for high efficiency coupling between the mixer and the radiation it is intended to detect. Table 1 shows the reported results of a variety of SIS mixers and receivers along with the coupling structure that each one uses.

Table 1. Summary of some of the best reported SIS receiver results. The bold lines separate the results into frequency ranges. Within a frequency range, the results are listed in order of increasing T_{RECDSB}.

Rf (GHz)	T_{REC} DSB (K)	T_{MIX} DSB (K)	Gain DSB (dB)	SIS material, size, configuration	Coupling (waveguide or antenna shape)	Reference
230	48	38	−2.6	0.25 sq. micron Nb	waveguide	[13]
230	48			Nb	waveguide	[11]
230	80	60	−2	PbBi alloy	waveguide	[7]
240	100			Nb	waveguide	[47]
228	114			PbInAu submicron	waveguide	[6]
230	116			PbInAu submicron	spiral	[8]
241	153	85	−7.5	PbInAu submicron	waveguide	[5]
228	163			PbInAu submicron	waveguide	[6]
230	200		−8	PbInAu submicron	waveguide	[10]
220	250	25	−9	SIN! (NOT an SIS)	waveguide	[48]
345	150			PbInAu submicron	waveguide	[21]
345	200			Nb	spiral	[42]
345	215			PbInAu submicron	spiral	[8]
342	214			3 PbBi in series	quasioptic	[24]
312	275		−9.5	Nb/PbInAu	waveguide	[22]
492	171	114	−9	0.25 sq. micron Nb	waveguide	[20]
426	220			Nb	spiral	[42]
490	420	240	−10	Nb	twin slot	[23]
525	470			PbInAu submicron	spiral	[8]
492	500			Nb	spiral	[42]
761	1100			PbInAu submicron	spiral	[8]

4.3. Waveguide SIS mixers

Until 1985, all SIS mixers used waveguide coupling structures. The rf input side of the mixer is almost always coupled to a scalar feedhorn [45, 46] which provides a very high quality Gaussian beam pattern. The waveguide behind the mixer usually contains a movable back short which can help tune out the parasitic reactances of the SIS and its mounting structure. In some designs, a second waveguide tuner can be included to increase the range of tuning which is possible. In other designs, no mechanical tuning is necessary.

A full height rectangular waveguide has dimensions a little smaller than $1/2 \times 1/4\ \lambda_0$ where λ_0 is the free-space wavelength at f_{rf}. At 500 GHz, this waveguide is quite small, $300 \times 150\ \mu m$. It is hard to say what the upper frequency limit is for a waveguide design. SIS's in waveguides

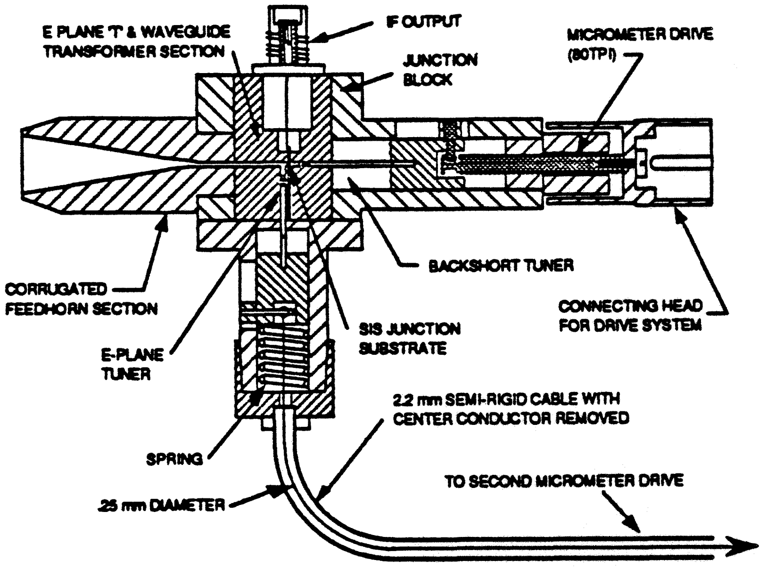

Figure 3 [6]. The two-tuner waveguide design which has been implemented for 230, 345, and 492 GHz band mixers.

are the most sensitive available mixer at 500 GHz Walker, 1991 #134]. It seems clear that waveguide designs will be attempted to at least 800 GHz.

The good features of waveguide designs are summarized. They provide excellent control over the rf source impedance seen by the SIS, either through fixed or mechanically tuned structures. They have excellent beam patterns capable of high efficiency coupling to radio telescopes and other signal sources.

4.3.1. Ellison's Waveguide Mixer

Some of the lowest noise SIS receivers for the 200 to 500 GHz frequency range [13, 21, 20] have been built at the California Institute of Technology using a mixer designed by Ellison [6]. This design, shown in fig. 3, includes two movable waveguide shorts, one behind the junction (back-short), and one in a waveguide tee in the E-plane wall of the waveguide near the junction (E-plane tuner). The SIS is mounted across the E-plane of the waveguide. One side of the SIS is shorted directly to the mixer block. The other side is coupled through an rf-choke structure to the IF and dc-bias circuits. In later designs, a symmetric mount is designed so that the ground connection is made at the end of an rf-choke.

This design has been verified and improved through the use of microwave scale modeling [49]. These models showed that the rf impedance seen by the SIS can be tuned over more than half the area of a Smith chart at almost all frequencies in the waveguide band. This modeling also demonstrated the critical importance of the placement of the SIS in the waveguide. The SIS must be centered in the waveguide to avoid extra reactance due to coupling to a higher order waveguide mode.

In all of the mixers based on Ellison's design, a great amount of attention has been paid to the IF matching circuit. This circuit is designed for two criteria: 1) transform the 50 Ω IF amplifier to a higher impedance, 100 to 200 Ω, at the SIS and 2) provide a low impedance at the SIS at frequencies outside the desired IF band. The first criterion improves the coupled gain of the SIS mixer since its IF output impedance is very high. The second criterion protects the SIS from IF saturation [50, 51].

4.3.2. Round Waveguide Mixer

An early attempt at designs that would be appropriate for high frequency scaling is Woody's round waveguide mixer [4]. Mixers based on this design have been built for 115 GHz [4], 230 GHz [5], and 345 GHz [22]. This design is relatively easy to scale to high frequencies. The round waveguide is fabricated by drilling the proper sized hole in a block. The rf choke is built into the mixer block. The SIS junction has no rf choking or any other frequency dependent structures on it, so the chip can be made very small. While the sensitivity of the round waveguide mixers is good, the greater complexity of the other designs discussed here is clearly justified by their lower noise temperatures.

4.3.3. IRAM Mixer

SIS mixers are built at the *Institut de Radio Astronomie Millimétrique* (IRAM) for use on European radio telescopes. The IRAM mixer block uses a reduced height rectangular waveguide with the SIS junction mounted across its E-plane. The reduced height waveguide provides a lower rf input impedance than full height waveguide, and eliminates resonant coupling to higher order modes which trouble Ellison's design. There is a single mechanical tuner, a backshort in the waveguide behind the SIS. The rf choke is fabricated integrally with the SIS and is symmetric around the junction: it is the basis for the rf choke structure now used in Ellison designed mixers. IRAM mixers have been built for 100 GHz [19] and 230 GHz [7, 47]. An SIS mixer is now being

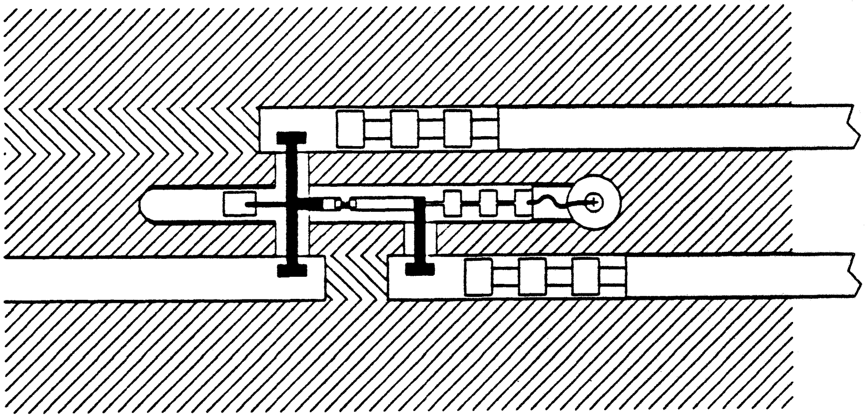

Figure 4 [11]. The NRAO-401 170-260 GHz mixer. The center channel contains microstrip circuitry including the SIS junctions with inductive tuning. The channel on the left is a waveguide carrying the signal and LO into the mixer. The top and bottom channels on the right are waveguides containing movable shorts for tuning. Stripline to waveguide coupling structures are shown in solid black.

developed for 345 GHz [47]. The simplicity and success of the IRAM design make it a good candidate for higher frequency operation.

4.4. Waveguide-Substrate Mixers

A number of mixer designs use a mechanically simple waveguide design to couple input radiation to a microstrip or coplanar transmission line built on a dielectric substrate. Critical rf circuit components in these mixers are fabricated photolithographically. It is easier to fabricate small components this way than to machine them into a waveguide block. Because of this, the approach is very promising for higher frequency mixers. These designs have been fabricated up to 230 GHz with excellent results. They should perform equally well at higher frequencies in the future. A few of these designs are presented below.

4.4.1. NRAO-401

The National Radio Astronomy Observatory makes a wide variety of receivers for radio astronomy in the US. Their NRAO-401 SIS mixer is shown in fig. 4 [11]. The rf is coupled from an input waveguide into stripline circuit through a broadband transition very similar to commercial waveguide to coaxial transitions available at much lower frequencies. Two adjustable waveguide tuning elements are also coupled to the circuit through similar probes to provide series and parallel reactances to the SIS. This mixer's sensitivity in a 230 GHz DSB receiver is the best currently available. A similar mixer is part of a 40 K DSB receiver at 100 GHz [9]. Both of these mixers can be tuned for SSB operation with 20 dB image rejection.

4.4.2. NRAO Tunerless Mixer

Another NRAO SIS mixer achieves 40-80 K DSB receiver temperatures over the entire WR-10 waveguide band, 75-110 GHz, without any mechanical tuning [11]. As in the NRAO-401, the waveguide to stripline transition couples radiation from the input waveguide to the substrate circuit. The stripline radiation makes a second transition to coplanar waveguide before it reaches the SIS and its integrated tuners.

4.4.3. Yale Waveguide-Microstrip Mixer

In this design, the input waveguide is coupled to a microstrip circuit with a 4-section Chebyshev single ridge transformer [39]. Nearly full WR-10 band coverage is achieved with no mechanical tuning. Circuits with microstrip inductive compensation of the SIS capacitance were investigated, but the lowest noise temperatures for this mixer were achieved without inductive tuning. Because of its simple mechanical design, this mixer is a good candidate for scaling to higher frequencies.

4.5. Quasioptic SIS mixers

An interesting alternative to waveguide coupling is shown in fig. 5. The SIS is fabricated integrally with a planar antenna. The SIS-antenna is placed on a hyperhemispherical lens. The lens focuses the input radiation into the center of the SIS-antenna which earns this scheme the name "quasioptic." A comprehensive introduction to the properties of antennas on dielectrics is given by Rutledge *et al.* [52]. The superconducting films from which the SIS-antenna is made are very good conductors, so the fabricated antennas will have low resistive losses despite the submillimeter frequencies involved. This low-loss property may not hold for $f_{rf} > 2\Delta/h$, about 700 GHz for niobium technology.

The planar antenna designs have the following positive features. Many of these mixers can be used over a few octaves of f_{rf}. The spiral and bowtie planar antennas are frequency independent both in their beam pattern and in their antenna impedance. The SIS-antennas are fabricated photolithographically so no waveguide or feedhorn must be machined. Large substrates can be used. If an SIS is to be placed across a waveguide, the SIS and its substrate must be much smaller

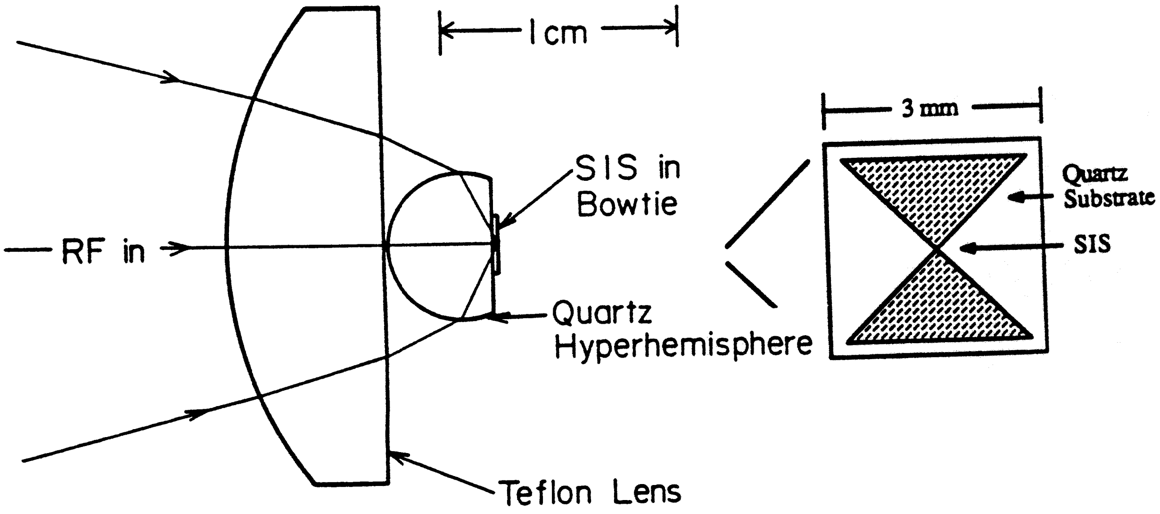

Figure 5 [33]. The bowtie dipole antenna is formed as an extension of the leads of the SIS diode. The radiation from this antenna is focussed into a fairly narrow beam by a hyperhemispherical lens placed up against the substrate. Further focussing is provided by a plastic lens

than an rf wavelength. An SIS-antenna, however, should actually be fabricated on a substrate which is bigger than a wavelength.

4.5.1. Spiral and Bowtie Antennas

The bowtie mixer in fig. 5 was improved on by using a spiral-shaped dipole antenna [8] like the one shown in fig. 2a. The mixer with spiral antenna had noise temperatures about half those of the bowtie mixer over the same large frequency range. This mixer has been used at the Caltech Submillimeter Observatory for radio astronomy at 115, 230, 345 and 492 GHz. Its beam couples to the telescope about as well as the beam from a waveguide receiver, resolving a difficulty with the bowtie design.

The spiral antenna has a much cleaner beam pattern than the bowtie, with sidelobe and pedestal structure at the -20 dB level. The cleaner beam is primarily due to the better radiation pattern of the spiral, but it is also helped by the use of a mirror less than 1 mm behind the SIS-antenna. The lower noise of the spiral SIS is attributable to its better beam pattern, as is its excellent coupling efficiency to the CSO radio telescope.

The submillimeter spiral SIS mixer has very recently been improved remarkably at the expense of its multi-octave bandwidth [42]. The design is similar to that shown in fig. 2b, but the

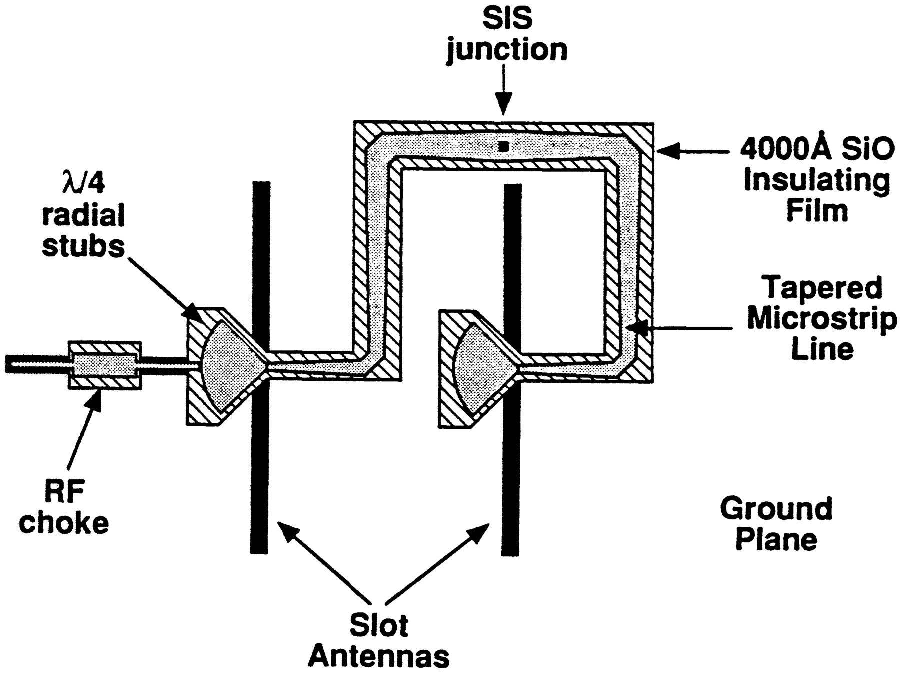

Figure 6. The planar antenna-SIS mixer of Zmuidzinas and LeDuc [23]. The entire structure is built on a niobium ground plane which is etched away to create the two slot antennas.

transformer is a more complicated two section Chebyshev design. The result is 75% or better coupling between the SIS and the spiral antenna in a one-octave rf band centered at 350 GHz. Receiver results using this mixer are included in Table 1. The fall-off in performance at 492 GHz is due to the low center frequency of this particular mixer. It should be a simple matter to adjust the design so that $T_{RECDSB} \leq 250$ K is achieved at 492 GHz.

4.5.2. Twin-slot antenna

Fig. 6 shows a different planar antenna design used in the mixer developed by Zmuidzinas and LeDuc [23]. This receiver is reported in further detail elsewhere in this conference publication. This design couples a single SIS junction to two planar slot dipole antennas as shown in fig. 6. Unlike the bowtie and spiral, the twin-slot is a resonant antenna, but it is reasonable to expect the rf bandwidth of this mixer to be similar to that of waveguide designs: about one-half octave.

The slot antennas have a low antenna impedance. They are coupled to the SIS through tapered transmission lines which reduce the impedance even further. Finally, the radiation impedance is reduced even further since the two slots appear in parallel across the SIS. The source admittance of radiation presented to the SIS at the design frequency is $Y_S \approx (4\ \Omega)^{-1}$. As a result, an SIS with a large junction area, 2.3 $(\mu m)^2$, can be used. The result is $T_{RECDSB} = 420$ K at

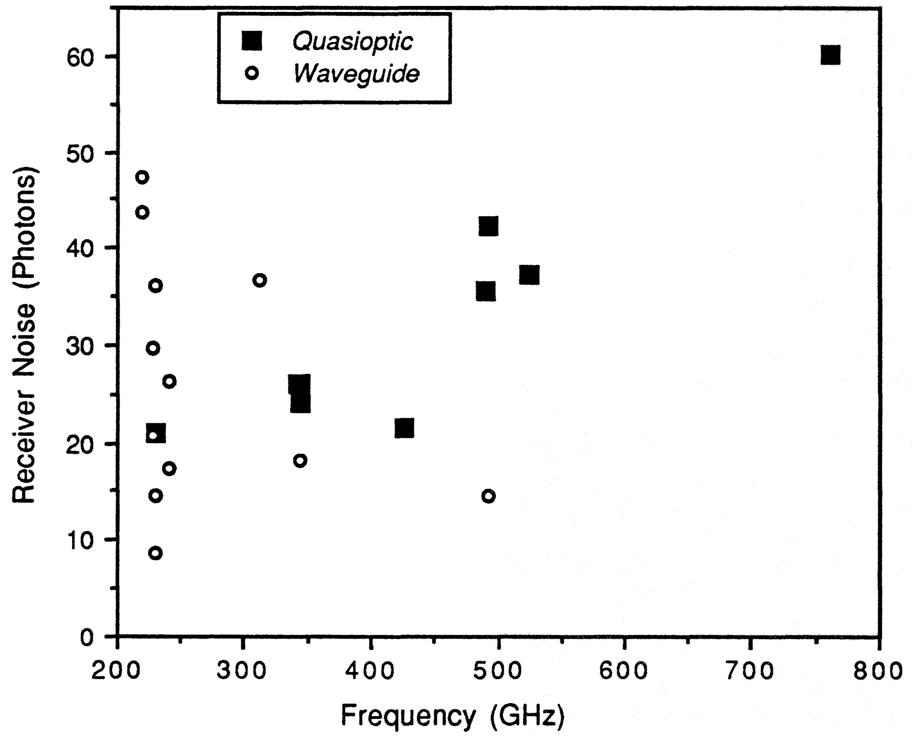

Figure 7. The noise of the receivers summarized in Table 1. Plotted is $T_{RECDSB}/(hf/2k_B)$. This normalizes the receiver noise to its quantum limit value.

492 GHz (the conference publication on this receiver should be reviewed for the most up to date information. It is reasonable to expect that the noise of this kind of receiver will drop quickly as more is learned about its design.

4.6. *Overall performance summary*

A summary of the best reported SIS receiver results is shown in fig. 7 and in Table 1. The most common results reported are T_{RECDSB}, so those are tabulated. DSB values of gain or mixer temperature are included in the table when they are quoted in the literature. Generally, SSB values can be estimated by doubling T_{RECDSB}, doubling T_{MIXDSB}, and subtracting 3 dB from the DSB Gain. The receiver noises in fig. 7 are normalized to the quantum limit of $N_{REC} = 1$ for an ideal photodiode mixer. The noise values achieved are many times this limiting value. However, these noise values represent a very great improvement over values available just a few years ago. It is reasonable to expect that they will continue to fall in the future.

4.7. *Unusual Mixers for Higher Frequencies*

This section is concluded with the mention of some unusual modes of superconducting mixer operation. None of these methods have been developed to the point that they are useful on a radio telescope. However, each method addresses problems with submillimeter SIS mixers in ways which may be useful in higher frequency superconducting mixers.

4.7.1. Harmonic mixing

A mixer can be designed so that it is sensitive to input signals at $f_S = n\, f_{LO} \pm f_{IF}$ where n is an integer. If $n \geq 2$, the mixer is said to be subharmonically pumped. Belitsky *et al.* investigated the gain of their spiral-transformer mixer with subharmonic pumps [53]. The mixer gain fell off slowly as n increased from 1 to 3. The advantages of subharmonic pumping include 1) it is easier to get powerful oscillators at lower LO frequencies and 2) the large separation between f_{LO} and f_S makes it easier to couple both of these to the SIS with high efficiency.

4.7.2. SIN junction mixer

If one of the superconducting sides of an SIS is replaced by a non-superconducting metal film, the resulting diode is a Superconductor-Insulator-Normal metal junction, or SIN. The SIN does not have as sharp a non-linearity in its IV as the SIS. But it also doesn't have any Josephson currents, which can be a problem in high frequency SIS mixers.

An SIN mixer at 230 GHz was built and tested by Blundell and Gundlach [48]. Compared to a similar SIS mixer, its gain was about 7 dB lower, but its mixer noise was quite low. Considering the very low noise IF amplifiers now available ($T_{IF} \approx 3$ K at 1.5 GHz), this is a very promising result. While it does not give any advantage over an SIS at 230 GHz, its lack of Josephson currents might make the SIN mixer useful at submillimeter wavelengths. Theoretical work on the SIN mixer operated both as a fundamental mixer [36, 54] and as a subharmonically pumped mixer [55] suggest it should be capable of $T_{RECDSB} < 100$ K up to 660 GHz.

4.7.3. Josephson effect mixing

While the Josephson effect is known to produce excess noise in submillimeter mixers, it is also capable of enhancing the gain of these mixers [33, 56]. While the current results for Josephson mixing show the noise increasing faster than the gain, the mixers tested are not designed to take advantage of the Josephson currents. Much work remains to be done on this type of mixer before it is known if it will be useful.

5. SUMMARY AND CONCLUSIONS

SIS mixers are used extensively for 100 to 500 GHz radio astronomical receivers. Many useful techniques have been developed for using SIS's at submillimeter wavelengths. The waveguide-feedhorn and the planar-antenna-lens (quasioptical) techniques provide excellent radiation beam patterns for SIS mixers. Integrated tuning elements including inductive components and transmission-line-transformers allow impedance matching of the SIS to both of these radiation coupling structures. SIS mixers using these techniques have been reviewed here.

6. ACKNOWLEDGEMENTS

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