ALMA Project Book, Chapter 5.

ALMA FRONT ENDS

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5 Alma Project Book. Front End

5.1 Introduction

This chapter of the Project Book describes the front ends that will be built for ALMA. As with all of the Project Book this chapter should be regarded as a "living document" subject to change at any time. Many of the details of the front end are undecided at the present time and will be included as the final design evolves. The present form of the front end is the result of efforts by several groups, each of which has contributed to the Project Book. From its conception it was recognized that the front end for ALMA would be quite different from any front end previously built for radio astronomy. Listed below are the major considerations that have driven the concepts behind the present front end design.

- For reasons of access, weight and all the usual reasons the decision was made at the start of the project to install the front end at the Cassegrain focus.
- Good performance over the complete range of frequencies to be covered by ALMA. This resulted in the frequency range of 31 GHz to 950 GHz being divided into ten separate bands. This division permits the optimization of both noise performance and optical coupling at all frequencies over the array's operating frequency band.
- Each frequency band will have two channels tuned to identical frequencies. The decision has been made to have these two channels receive two linearly polarized orthogonal signals.
- High reliability. It is recognized that building a front end that must be replicated at least 64 times is quite different from building a single front end for one telescope. High reliability is obviously a major consideration. It has been recognized that high reliability and the very best performance may not always be achievable together.
- The front end should be modular so that one easy to install self-contained receiver should cover that one particular frequency band. This was felt to be necessary to accommodate the desire to have groups in different locations produce receivers for the different bands. These self-contained receivers have become to be known as "cartridges".
- The front end itself, containing the ten cartridges should be one self-contained unit, easily removable from the antenna for servicing.
- The front end and all its components should be able to be produced, assembled and tested in a manner appropriate to the manufacture of front ends on this scale. It is recognized that the resulting design may be quite different from that produced for optimum performance on a single telescope.
- Servicing and all matters to do with installation on the antenna should be as easy as possible and appropriate to conditions at the high site.
- The front end should operate for long periods - around one year - with no maintenance. Experience at various telescopes in operation for many years suggest that this is a realistic goal although it was felt that this requirement ruled out the use of a "hybrid" cryostat involving the use of liquid helium.

5.2 Specifications

The document *Specifications for the ALMA Front End Assembly* (latest version) contains the detailed specifications. These have been approved by the AEC with a pending change request regarding the extension of band 3 down to 84 GHz. The main specifications are:

- Frequency coverage: from 31.3 to 950 GHz in 10 bands (see Table 5.1)

- simultaneous reception of two orthogonal polarizations
- receiver noise between 6 and 10 times *hn/k* over 80% of the band, with a goal of achieving 3 to 8 times *hn/k*, depending on the band
- IF bandwidth 8 GHz total per polarization
- observations at one frequency at a time (no dual frequency obervations)
- inclusion of a water vapour radiometer using the 183 GHz line for phase correction.

For details, see the full *Specifications for the ALMA Front End Assembly* (latest version).

Table 5.1 – Frequency bands for ALMA

Band	from (GHz)	to (GHz)
1	31.3	45
2	67	90
3	89*	116
4	125	163
5	163	211
6	211	275
7	275	370
8	385	500
9	602	720
10	787	950

* change request to 84 GHz underway

5.3 Overall System Description

The following is a brief description of the overall front end system. Details may be found in the relevant sections of the chapter. The receiver consists of a circular dewar 1.0 m in diameter and 0.7 m in height. The individual receivers (cartridges) are inserted into the bottom of the circular dewar. LO, IF and circuit connections are made to cartridges from the bottom of the cartridge: the millimeter/sub-millimeter signal enters the top of the cartridge via a vacuum window and infra-red filter. The entrance to the various frequency band cartridges is in the focal plane of the antenna so frequency selection is achieved by adjusting the telescope pointing. This very simple configuration is shown in Figure 5.1

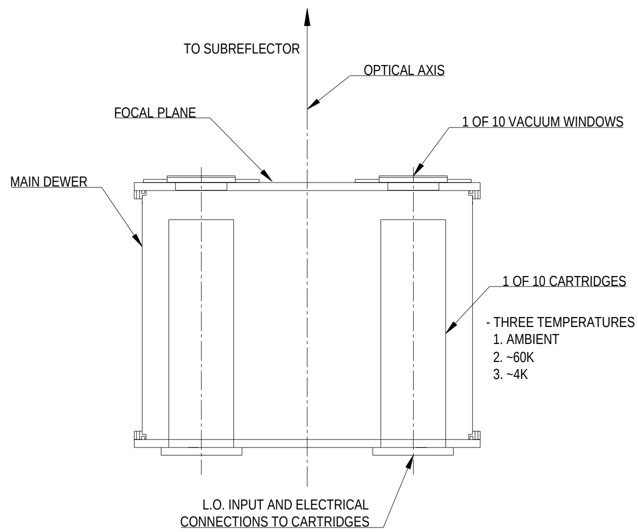


Figure 5.1

The necessary IF processing, various control circuits and computer interfaces will be packaged external to the dewar with the configuration yet to be decided. The overall configuration of the front end is illustrated in block diagram form in Figure 5.2 (the front end configuration) and Figure 5.3 (the cartridge configuration).

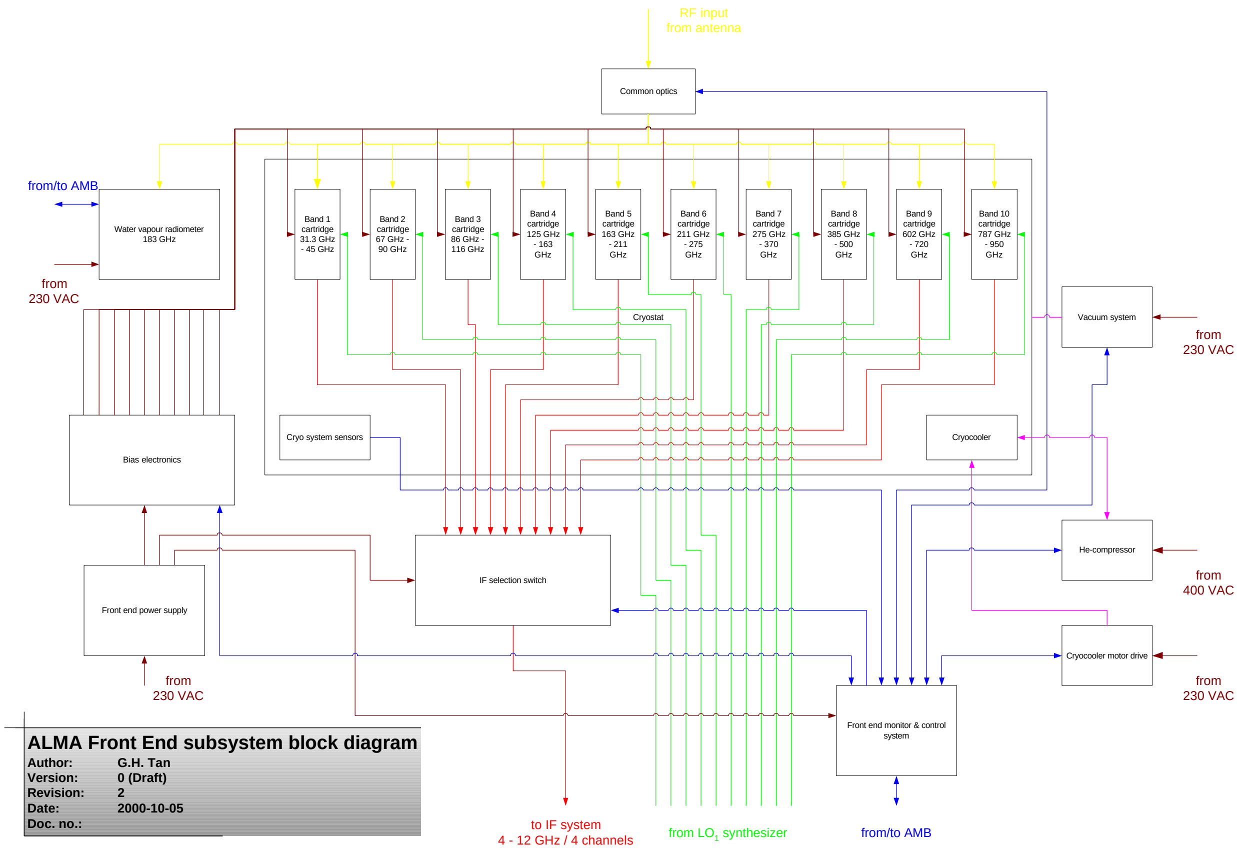
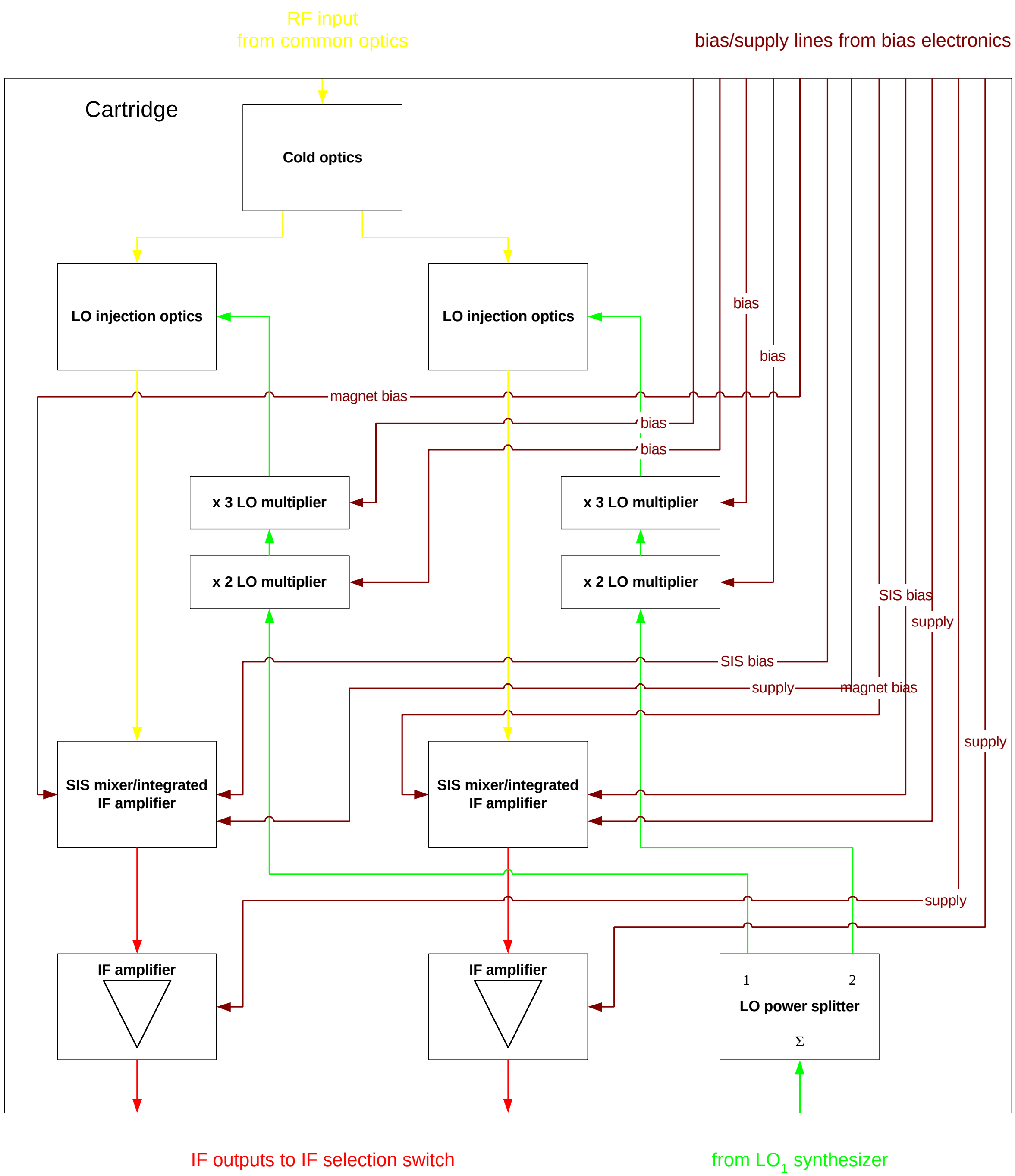

RF input
from antenna
Common optics
from/to AMB
Water vapour radiometer
183 GHz
from
230 VAC
Band 1
cartridge
31.3 GHz
- 45 GHz
Band 2
cartridge
67 GHz -
90 GHz
Band 3
cartridge
86 GHz -
116 GHz
Band 4
cartridge
125 GHz
- 163
GHz
Band 5
cartridge
163 GHz
- 211
GHz
Band 6
cartridge
211 GHz
- 275
GHz
Band 7
cartridge
275 GHz
- 370
GHz
Band 8
cartridge
385 GHz
- 500
GHz
Band 9
cartridge
602 GHz
- 720
GHz
Band 10
cartridge
787 GHz
- 950
GHz
Cryostat
Vacuum system
from
230 VAC
Bias electronics
Cryo system sensors
Cryocooler
He-compressor
from
400 VAC
IF selection switch
Front end power supply
Cryocooler motor drive
from
230 VAC
from
230 VAC
Front end monitor & control
system
ALMA Front End subsystem block diagram
Author: G.H. Tan
Version: 0 (Draft)
Revision: 2
Date: 2000-10-05
Doc. no.:
to IF system
4 - 12 GHz / 4 channels
from LO1 synthesizer
from/to AMB

Figure 5.2



ALMA band 9 cartridge block diagram

Author:	G.H. Tan
Version:	0 (Draft)
Revision:	3
Date:	2000-10-05
Doc. no.:	

Figure 5.3

5.4 The optical arrangement

(See separate sub-chapter on Optics in Project Book Table of Contents)

5.5 The dewar and Cryogenic Cooler

(See separate chapter on Cryogens in Project Book Table of Contents)

5.6 Receiver Band Cartridges

5.6.1 Introduction

The concept of receiver cartridges is being developed for various reasons. The idea of a millimeter front end consisting of various well defined inserts is not new and was developed at NRAO many years ago. For the ALMA receivers the idea of each receiver band being a single unit, testable separately of the main receiver Dewar was particularly appealing given the participation of various groups geographically separated and the desire of these groups to be responsible for different receiver bands. The cartridge approach also minimizes the number of interfaces (optical, mechanical, electrical and thermal) and allows that a cartridge may be built and tested in one location and installed in the main front end dewar later. The constraints on cartridge size are outlined in *** along with drawings of the basic cartridge. The *ALMA Scientific Advisory Committee (ASAC)* has identified four receiver bands out of ten as first priority for development and installation. These are bands 3 (89 – 116 GHz), 6 (211 – 275 GHz), 7 (275 – 370 GHz) and 9 (602 – 720 GHz). The design approaches for these four initial bands are described in the following sections.

5.6.2 Band 3 Cartridge development at NRAO

Last revised on November, 05 – 2000 by A.R. Kerr, S.-K. Pan and John Webber

Revision History: 2000-10-05: New

5.6.2.1 Introduction

This band is presently defined as covering 89-116 Ghz. However there is a change order in process to change the lower end of this band to 84 Ghz. In recent years HFET amplifiers have been developed which meet the ALMA specifications with one exception and would be most attractive to use. Since the ALMA receivers are intended for both interferometric and single-dish total power observations the radiometric stability of the receivers is important. Based on the work of Wollack and Pospiezalsky [?] the so called 1/f noise produced by a wideband HFET amplifier would exceed the ALMA specifications. This problem has been well summarized by Webber (see section 5.6.2.2.3). Due to this potential problem work had progressed on the development of a fixed tuned SIS mixer for band 3 as described below.

5.6.2.2 SIS Mixer Development for band 3

5.6.2.2.1 Summary

This section describes the SIS mixer development plan for the ALMA front-ends for Band 3, nominally 90-116 GHz, for which the science group has requested assessment of the feasibility of extension to 86-116 GHz. The primary driver for this development is the 1/f gain noise of HFET receivers (discussed below). The goals for the design and development phase are:

1. carry out a thorough study on the feasibility of developing balanced sideband-separating mixers with integrated IF amplifiers meeting the ALMA specifications,
2. develop and evaluate a fully-integrated (MMIC) fixed-tuned waveguide mixer and use it as a building block in the balanced and sideband separating mixer, and
3. provide technical and budgetary information gathered in this study to ALMA management and scientific advisory committee as one of the basis of choosing SIS or HFET receivers for this band. If it is decided to use SIS receivers in this band, the goals for the construction phase are to mass-produce SIS mixers with repeatable performance at minimum total cost.

Table 5.2 - SIS Receiver Specifications

Item	Specification
Receiver noise temperature	Noise sufficiently low to produce single sideband receiver noise referred to the vacuum window of 60 K over 80% of band and 80 K at any frequency
Frequency band covered	Band 3, 90-116 GHz, extended to 86-116 GHz if possible
IF bandwidth	Minimum of 4 GHz total, falling in band 4-12 GHz; want 8 GHz for each sideband if possible
Linearity	TBD
Configuration	Balanced operation, sideband separation > 10 dB, no mechanical tuners

5.6.2.2.2 Development

5.6.2.2.2.1 Design Requirements

In order to meet the receiver specifications listed in Table 5.2, the following properties are required in Band 3 SIS mixers:

- Low mixer noise temperature.
- Low mixer conversion loss (~0 dB DSB). While gain is possible in SIS mixers, substantial conversion gain is undesirable because of the reduced dynamic range and greater possibility of out-of-band instability.
- High saturation power. Receivers should be capable of performing solar observations.
- Wide RF bandwidth (minimum of 26 GHz total, from 90 to 116 GHz, but extended to 30 GHz total, from 86 to 116 GHz, if possible).
- Wide IF bandwidth (minimum of 8 GHz total, from 4 to 12 GHz).
- A moderately well matched input.
- Operation into a 50-O IF amplifier with no matching impedance transformer is desirable. SIS mixers with matched output tend to have poor input match and, in certain cases, may have input reflection gain, which may increase the baseline ripples and the receiver's instability.

5.6.2.2.2.2 Single-Junction vs. Array

Theoretically, the performance of an N-junction array is the same as that of a single junction, which has the same overall impedance, provided that

- current is in phase all along the array and
- that all of the junctions of the array are identical.

The advantages of using N-junction arrays are:

- a greatly increased dynamic range (proportional to N^2),
- easy suppression of Josephson-effect noise
- less susceptibility to electric transients and
- easier fabrication (better yield).

The disadvantages of using arrays are:

- some experiments have shown that, contrary to the theoretical predictions, array mixers may have higher noise temperature than single-junction mixers and
- it requires N^2 more LO power to operate.

Since the NRAO is experienced in developing and operating quantum-limited low-noise array mixers in this frequency band and sufficient LO power is not an issue in Band 3, we have decided to use arrays in this band.

5.6.2.2.2.3 MMIC Design vs. Waveguide Hybrids

There are many ways to construct balanced sideband-separating mixers in the millimeter- and submillimeter-wave bands.

Two designs, a single-chip (MMIC) design developed at NRAO [1-3] and a design based on waveguide hybrids reported in ALMA Memo 316 [4], are in particular suitable for ALMA balanced sideband separating mixer development work. However, for Band 3, because the large size of single-chip balanced sideband-separating mixers will permit very few mixers per wafer, the approach using waveguide hybrids may be preferable to the MMIC approach.

5.6.2.2.2.4 Junction Parameters

Kerr and Pan [5] and Ke and Feldman [6] have developed SIS mixer design procedures. At 100 GHz, both procedures give similar optimum source and load conductance and junction ? R_NC product. Table 5.3 lists the junction parameters calculated using the design rules outlined in [5] with a source impedance of 35 O and load impedance of 50 O, a specific capacitance C_S = 65 fF/μm^2, R_NI_C = 1.8 mV and ? R_NC = 3.5 at 115 GHz.

Table 5.3 - Band 3 Device Parameters for UVA=s Niobium Trilayer Circuit Process

Jc	2,500 A/cm^2
Junction size (diameter)	2.3 μm
Normal Resistance of the Array	70 O
Cs	65 fF/μm^2
SiO dielectric constant	5.7
I2 (SiO)	2,000 D

M3	4,000 D
Pd/AU	300 D

5.6.2.2.2.5 Mixer Design

A fully integrated (MMIC) fixed-tuned 86-116 GHz SIS waveguide mixer, similar to the NRAO 373 mixer [7], is currently being developed at the CDL for ALMA Band 3. Special design efforts have been made to meet ALMA's specifications. The circuit parasitics (capacitance and inductance) seen at the mixer's IF port have been minimized using a circuit layout similar to that described in [7] to meet ALMA's IF bandwidth specification. An additional RF matching circuit has been implemented to increase the RF bandwidth.

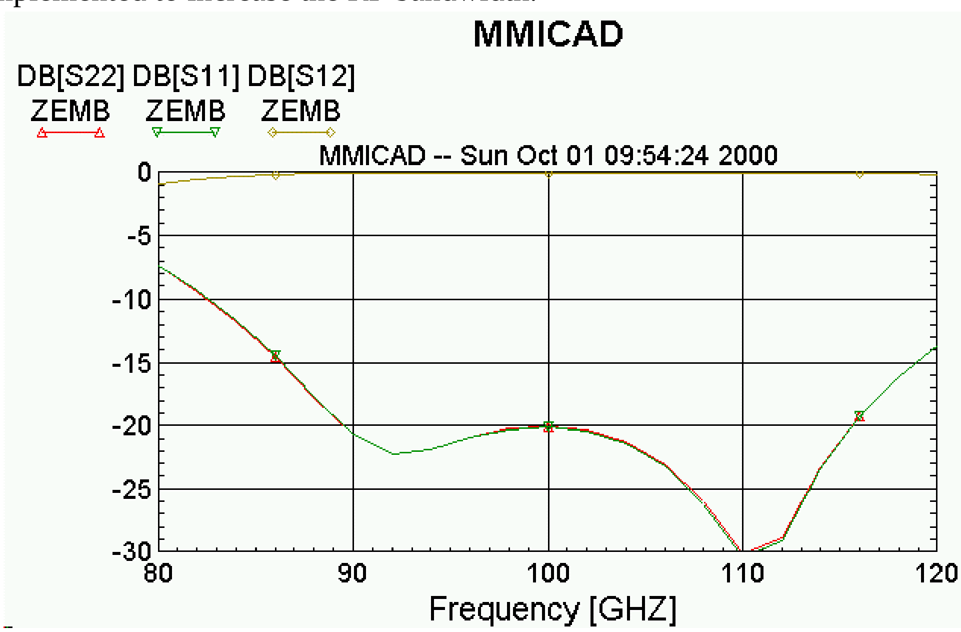


Figure 5.4 - Return loss of the coupling network to the SIS array. The return loss is the match seen at the 50 O waveguide probe to a 35 O optimum array source impedance.

Initial circuit analysis using MMICAD [8], shown in Figure 5.4, shows that it is possible to design a coupling network to provide good matching between waveguide probe and the array's optimum source admittance over the entire ALMA Band 3 frequency range. The RF embedding admittance seen by the array is shown in Figure 5.5.

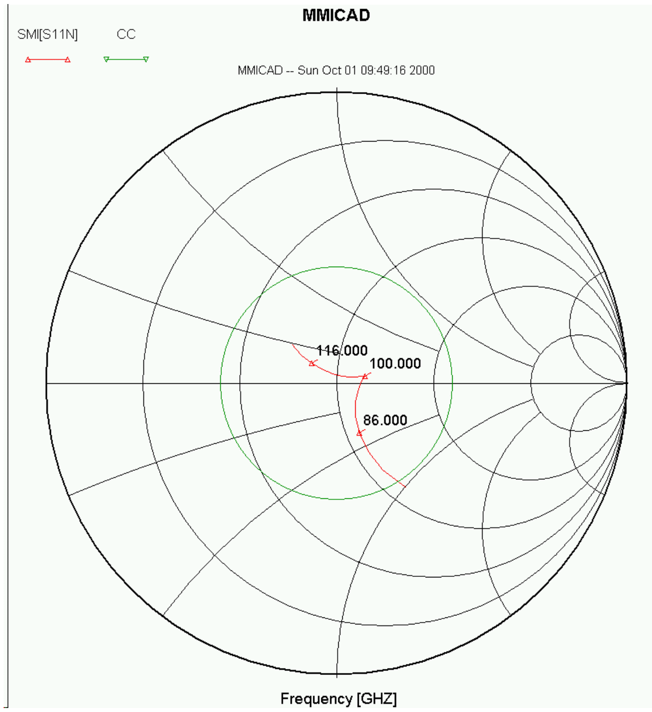


Figure 5.5 - RF embedding admittance seen by the array. The junction capacitance is taken as part of the embedding circuit. The circle is at |?| = 0.4. The Smith chart is normalized to the optimum source conductance.

The Smith chart is normalized to the optimum source admittance for the array, 0.0286 mhos in the present case. The junction capacitance is taken as part of the embedding circuit in this calculation. The circle at |?| = 0.4 indicates the range of embedding admittance within which acceptable SIS mixer performance will be attained.

5.6.2.2.2.6 Band 3 Milestones

Table 5.4 - Band 3 building block mixer milestones

shows the proposed development schedule for Band 3 SIS building block mixer:

Table 5.4 - Band 3 building block mixer milestones

Finish mixer circuit analysis	2000-11-30
Mask layout	2000-12-21
Mask fabrication	2001-01-15
Junction fabrication by UVA	2001-02-15
Mixer block fabrication	2001-02 -15
Mixer evaluation	2001-03-15

5.6.2.2.3 1/f Gain Fluctuations

Since the ALMA receivers are intended to perform duty both for interferometric and for single-dish total power observations, the radiometric stability of the receivers is important. M. Pospieszalski of NRAO has already developed a wideband 68-116 HFET amplifier with noise performance which nearly meets the ALMA specification. However, based on work by Wollack [9] and Wollack and Pospieszalski [10], it may be calculated that the 1/f gain fluctuation of a single-channel radiometer (no switching) would produce total power fluctuation of about $3 \cdot 10^{-4}$ in one second, exceeding the ALMA receiver specification of $1 \cdot 10^{-4}$ in one second. Preliminary results on a 230 GHz laboratory SIS receiver indicate that it meets the ALMA specification; a detailed investigation is in progress.

5.6.2.2.4 Section References

[1] A. R. Kerr and S.-K. Pan, ADesign of planar image-separating and balanced SIS mixers,@ *Proceedings of the Seventh International Symposium on Space Terahertz Technology*, pp. 207-219, 12-14 March 1996. Available as ALMA Memo151 at http://www.alma.nrao.edu/memos/html-memos/alma151/memo151.pdf

[2] A. R. Kerr, S.-K. Pan, A. W. Lichtenberger, N. Horner, J. E. Effland and K. Crady, AA single-chip balanced SIS mixer for 200-300 GHz,@ *Proceedings of the 11th International Symposium on Space Terahertz Technology*, May 1-3, 2000. Available as ALMA Memo 308 at http://www.alma.nrao.edu/memos/html-memos/alma308/memo308.pdf

[3] A. R. Kerr, S.-K. Pan and H. G. LeDuc, AAn integrated sideband-separating SIS mixer for 200-280 GHz,@ *Proceedings of the Ninth International Symposium on Space Terahertz Technology*, pp. 215-221, 17-19 March 1998. Available as ALMA Memo 206 at http://www.alma.nrao.edu/memos/html-memos/alma206/memo206.pdf

[4] S. M. X. Claude, C. T. Cunningham, A. R. Kerr and S.-K. Pan, ADesign of a sideband-separating balanced SIS mixer based on waveguide hybrids,@ ALMA Memo 316, available at http://www.alma.nrao.edu/memos/html-memos/alma316/memo316.pdf

[5] A. R. Kerr and S.-K. Pan, ASome recent developments in the design of SIS mixers,@ *Int. J. Infrared Millimeter Waves*, vol. 11, no. 10, pp. 1169-1187, Oct. 1990.

[6] Q. Ke and M. J. Feldman, AOptimum source conductance for high frequency superconducting quasi-particle receivers,@ *IEEE Trans. Microwave Theory Tech.*, vol. MTT-41, no. 4, pp. 600-604, April 1993.

[7] A. R. Kerr, S.-K. Pan, A. W. Lichtenberger and H. H. Huang, AA tunerless SIS mixer for 200-280 GHz with low output capacitance and inductance,@ *Proceedings of the Ninth* International Symposium on Space Terahertz Technology, pp. 195-203, 17-19 March 1998. Available as ALMA Memo 205 at http://www.alma.nrao.edu/memos/html-memos/alma205/memo205.pdf

[8] MMICAD is a microwave integrated circuit analysis and optimization program, and is a product of Optotek, Ltd., Ontario, Canada K2K-2A9.

[9] E. J. Wollack, AHigh-Electron-Mobility Transistor Gain Stability and it Design Implications for Wide Band Millimeter Wave Receivers@, 1995, *Rev. Sci. Instrum.*, vol. 66, no. 8, pp. 4305-4312.

[10] E. J. Wollack and M. W. Pospieszalski, ACharacteristics of Broadband InP Millimeter-Wave Amplifiers for Radiometry@, 1998, *IEEE MTT-S Digest*, pp. 669-672.

5.6.2.3 Orthomode Transducer for band 3.

As mentioned previously each ALMA band is divided into two channels, each channel responding to a linear polarization with the two polarizations being orthogonal. For the lower frequency bands we are developing waveguide orthomode junctions based on the Biofort junction. Ed Wollack, now at NASA Goddard has pioneered this work (We need references and possibly results here). We now have good results from such an orthomode transducer for band 3 and are working now on a similar design for band 6. An outline drawing of the OMT is given below.

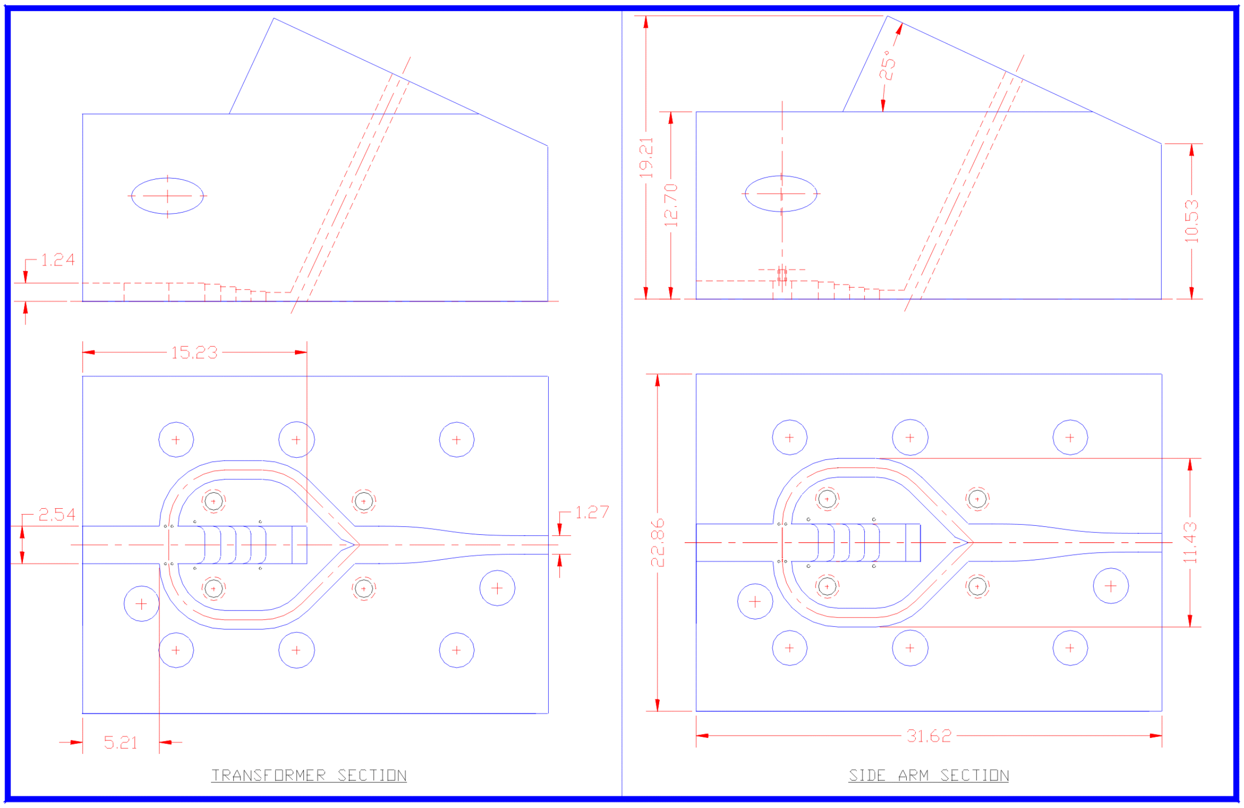


Figure 5.6

5.6.2.4 Band 3 Cartridge outlines.

A preliminary outline of a cartridge design that will satisfy the mechanical dimensions of the present cartridge design is given below.

Figure 5.7

5.6.3 Band 6 SIS mixer development at NRAO

Last revised on November, 05 – 2000 by A.R. Kerr, S.-K. Pan and John Webber

Revision History: 2000-10-05: Revised from 1999 MMA version for ALMA.

5.6.3.1 Summary

This section describes the SIS mixers to be used in ALMA front ends for Band 6, 211-275 GHz. The goals for the design and development phase are to produce working prototypes of balanced, sideband-separating mixers with internal IF amplifiers (see section 5.6.4) meeting the general specifications. The goals for the construction phase are to produce large numbers of mixers with repeatable performance at minimum total expense.

Table 5.5 - SIS mixer specifications

Item	Specification
Receiver noise temperature	Noise sufficiently low to produce single sideband receiver noise referred to the vacuum window of 77K over 80% of band, 126K

	at any frequency
Frequency band covered	Band 6, 211-275 GHz
IF bandwidth	Minimum of 8 GHz total, falling in band 4-12 GHz; want 8 GHz for each sideband if possible—otherwise, 4 GHz per sideband is acceptable
Linearity	TBD
Configuration	Balanced operation, sideband separation >10 dB, no mechanical tuners

Table 5.6 - SIS mixer Band 6 milestones

First sideband-separating (SBS), balanced mixer tests	2000-10-30
Integration of SBS, balanced mixer with 4-12 GHz IF amplifiers	2001-03-01
Critical Design Review	2001-04-01
Beginning of production	2001-06-01

5.6.3.2 Performance

Figure 5.8 shows the DSB noise temperatures of SIS receivers reported in the last few years. The best fixed-tuned receivers have DSB noise temperatures in the range 2-4 hν/k up to ~700 GHz. Above ~700 GHz, receiver noise temperatures rise rapidly because of RF loss in the Nb conductors. Work on new materials is likely to improve high frequency results in the next few years (e.g., NbTiN for 700-1200 GHz).

Note that in calculating SSB system noise temperatures from DSB receiver noise temperatures, care must be taken to include the appropriate image input noise. The appropriate value of SSB receiver noise temperature is given (in the absence of window, lens, mirror, and IR filter losses) by:

$$\mathbf{T_{RSSB} = 2T_{RDSB} + T_{image}}$$

This formula applies to a SSB receiver composed of a DSB receiver with a sideband separating network at its input. Since $\mathbf{T_{RDSB}}$ presumably includes window plus IR filter plus horn loss, that will be included in both signal and image channels, so the value of $\mathbf{T_{RSSB}}$ above is pessimistic.

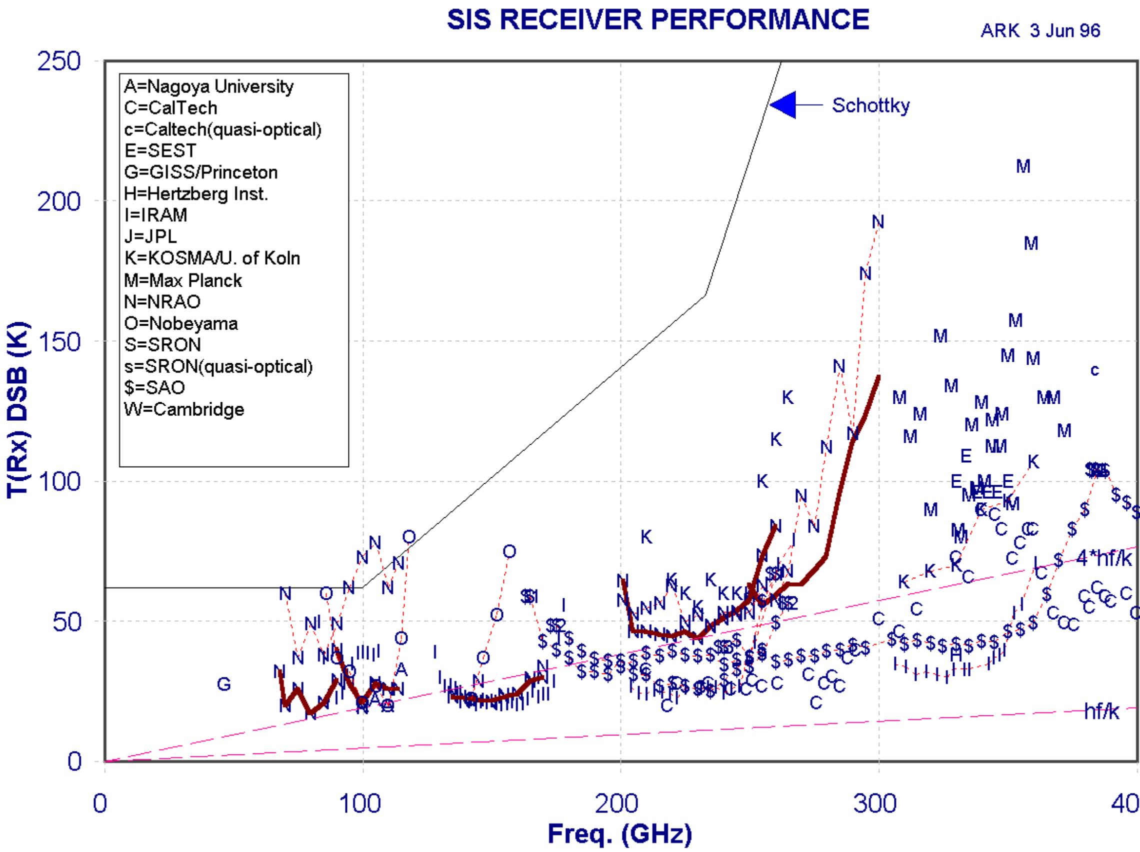


Figure 5.8 - Reported SIS mixer DSB receiver temperatures

Most of these receivers use a ~1.5 GHz IF, an exception being the SAO receivers which use 4-6 GHz. The IF for ALMA is chosen as 4-12 GHz to give the desired 8 GHz IF bandwidth. The best individual tunerless SIS receivers reported to date in the 150-400 GHz range have frequency ranges 1.37:1, 1.42:1, and 1.54:1. Their noise temperatures degrade quite precipitously beyond the band edges. In making the 64 receivers required for each band on ALMA, we cannot expect to achieve identical Tr vs. freq. characteristics, and the maximum bandwidth common to all 80 receivers will be somewhat less than that of the individual receivers. (Nb process control is something we are starting to work on with our SIS fabricators, but hitherto there has been little consideration given to such matters in SIS mixer production). It is hoped that by the time we start building the ALMA receivers we will be able to achieve a 1.5:1 common bandwidth, but until this is actually demonstrated we should be conservative to ensure we do not end up with unexpected gaps in the frequency coverage. This has governed the choice of frequency bands for the SIS receivers.

5.6.3.3 Development

5.6.3.3.1 Capacitively loaded coplanar waveguide

To achieve wide RF bands (an upper to lower frequency ratio of 1.3 or greater) without mechanical tuning, a fully integrated (MMIC) mixer design is desirable. The resulting "drop in" mixer chips are relatively easy to mount in blocks in which they are coupled to RF and LO waveguides. Conventional microstrip MMIC technology is difficult to use above ~100 GHz because of the very thin substrates necessary to prevent coupling to unwanted substrate modes. The use of coplanar waveguide (CPW) circuits allows a thick substrate, but is prone to odd-mode resonances excited by bends or near-by obstacles, and has poor isolation between adjacent lines. CPW also requires inconveniently narrow gaps when a substrate of low dielectric constant is used. To overcome these difficulties, we have developed capacitively loaded coplanar waveguide (CLCPW), a CPW with periodic capacitive bridges. The bridges are grounded at the ends, thus suppressing the odd mode, but they also add a substantial capacitance per unit length to the CPW, which allows desirable characteristic impedance levels to be obtained with convenient dimensions. Figure 5.9 shows a 200-300 GHz quadrature hybrid composed of CLCPW with periodic capacitive bridges.

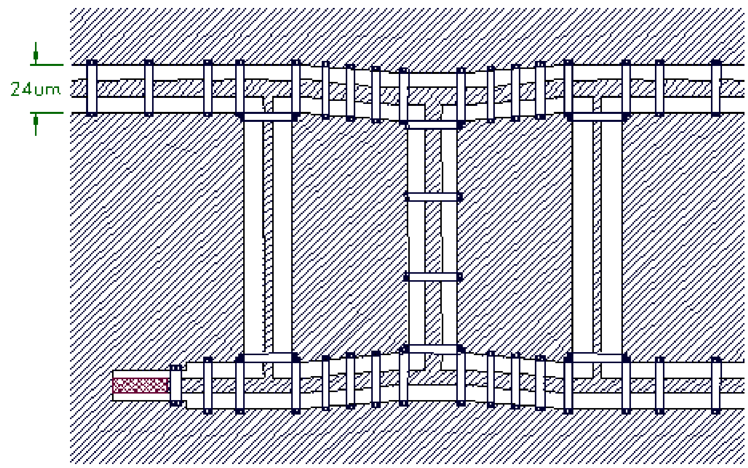


Figure 5.9 - A 200-300 GHz quadrature hybrid using capacitively loaded coplanar waveguide (CLCPW).

The bridges are 4 microns wide, and are connected to the ground plane at their ends. The fourth port (lower left) has a built-in matched termination. The substrate is 0.0035" fused quartz.

5.6.3.3.2 Sideband separating mixer

Even at the proposed site in Chile with its low atmospheric water vapor, atmospheric noise in the image band of an SIS receiver will add substantially to the system noise. The advantages of sideband separating mixers with their image terminated in a 4 K cold load have been discussed (see ALMA Memos 168 and 170), and we expect to use sideband separating mixers in at least the lower frequency SIS receivers. A developmental MMIC 211-275 GHz sideband separating mixer is shown in (Figure 5.10, Figure 5.11, Figure 5.12, Figure 5.13 and Figure 5.14). The IF outputs from the mixer are combined in an external quadrature hybrid which phases the down-converted signals from the upper and lower sidebands so they appear separately at the output ports of the hybrid. A useful property of the sideband separating SIS mixer is that the sidebands can be swapped between the two outputs simply by reversing the polarity of the bias on one of the component mixers.

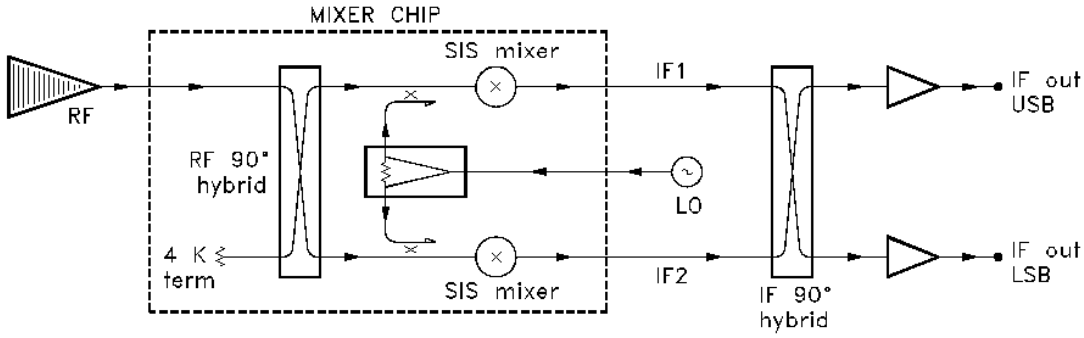


Figure 5.10 - Block diagram of an SIS sideband separating mixer

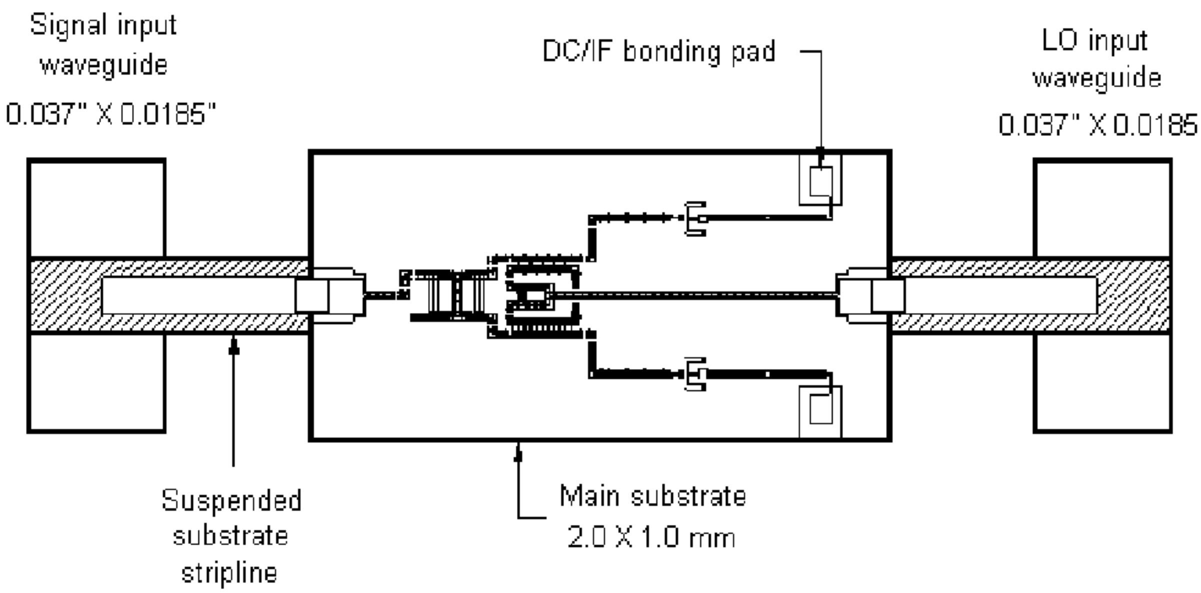


Figure 5.11 - 211-275 GHz sideband separating mixer, showing the signal and LO waveguides, suspended stripline coupling probes, and the main substrate.

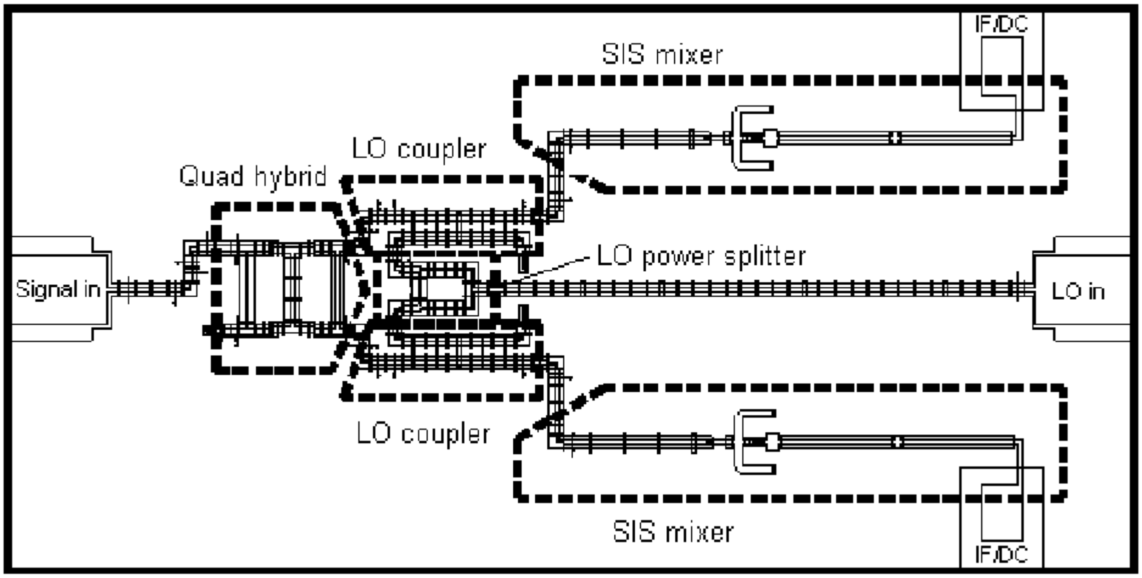


Figure 5.12 - Substrate of the 211-275 GHz sideband separating mixer, showing the main components.

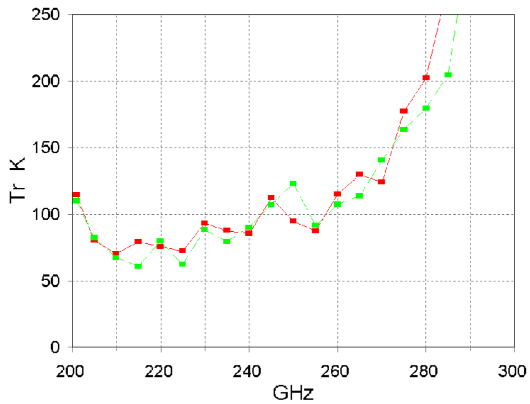


Figure 5.13 - Receiver temperature for the experimental mixer.

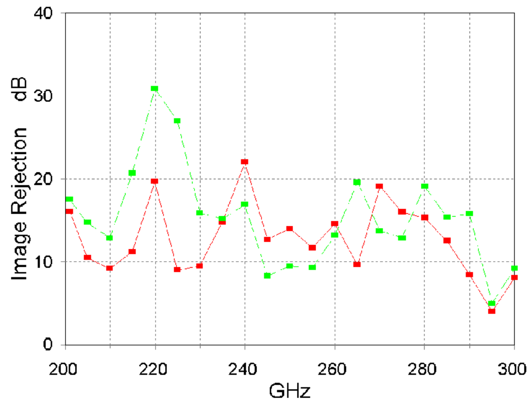


Figure 5.14 - Receiver sideband separation for the experimental mixer.

5.6.3.3.3 Balanced mixer

The use of balanced SIS mixers has two potential advantages for ALMA. Compared with the usual ~20 dB LO coupler or beam splitter in front of the mixer, a balanced mixer requires ~17 dB less LO power. This greatly eases the task of developing wideband tunerless LOs. The other benefit of a balanced mixer is its inherent rejection of AM sideband noise accompanying the LO. A MMIC balanced mixer design is shown in (Figure 5.15, Figure 5.16 and Figure 5.17).

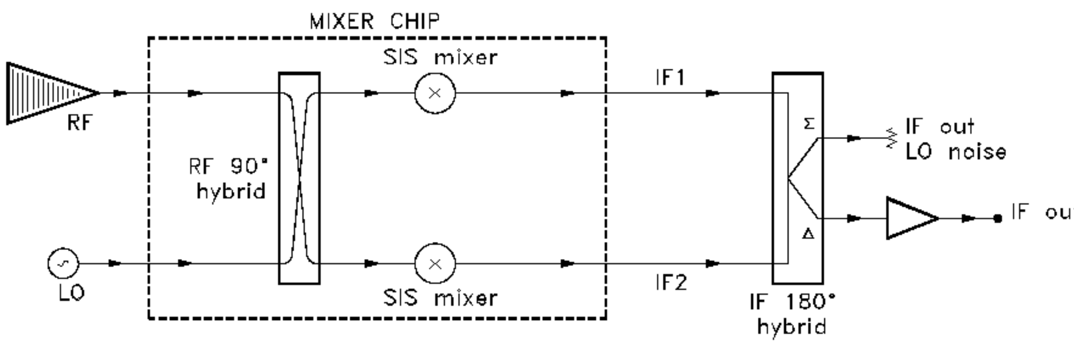


Figure 5.15 - Block diagram of a balanced SIS mixer.

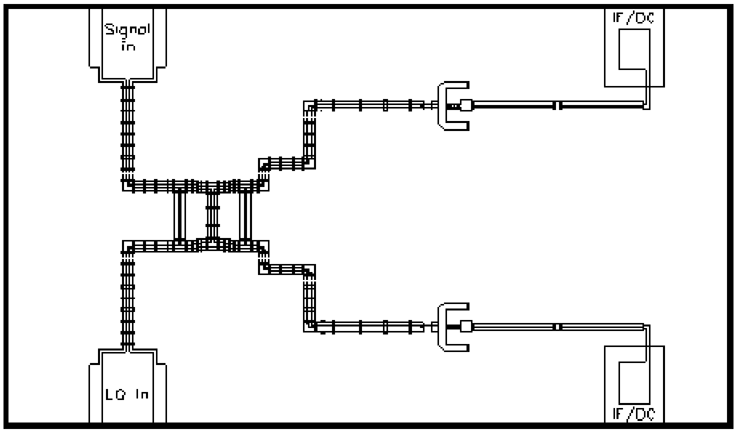


Figure 5.16 - Substrate of a 211-275 GHz balanced mixer, showing the quadrature hybrid and two SIS mixers.

ALMA Memo 308 describes the 211-275 GHz balanced mixer depicted in Figure 5.16. The measured noise temperature is shown *vs*. frequency in Figure 5.17. The first such chip tested was tuned slightly high due to normal variation of wafer parameters, but it exhibits good noise performance and LO noise rejection. The LO noise rejection was >10dB over the tuning range.

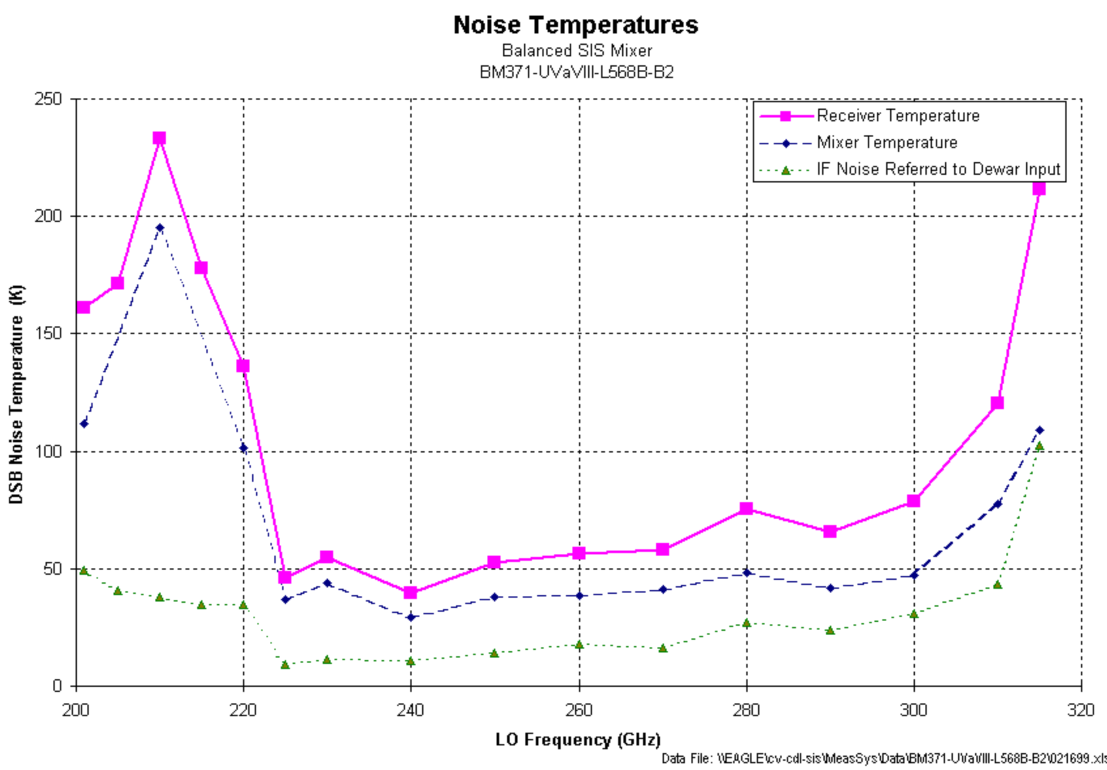


Figure 5.17 - Noise of a balanced SIS mixer.

5.6.3.3.4 Sideband-separating balanced mixers

Now that the designs of the sideband-separating and balanced mixers have been verified, we have designed and expect soon to test a mixer which incorporates both these features: a balanced, sideband-separating mixer. This will incorporate the circuit elements whose design has already been proven individually. This will produce for the MMA a mixer that requires a minimum of LO power, provides good immunity to LO noise, and substantially reduces the contribution to system noise of atmospheric noise in the unwanted sideband.

A photograph of a single MMIC chip is shown in Figure 5.18.

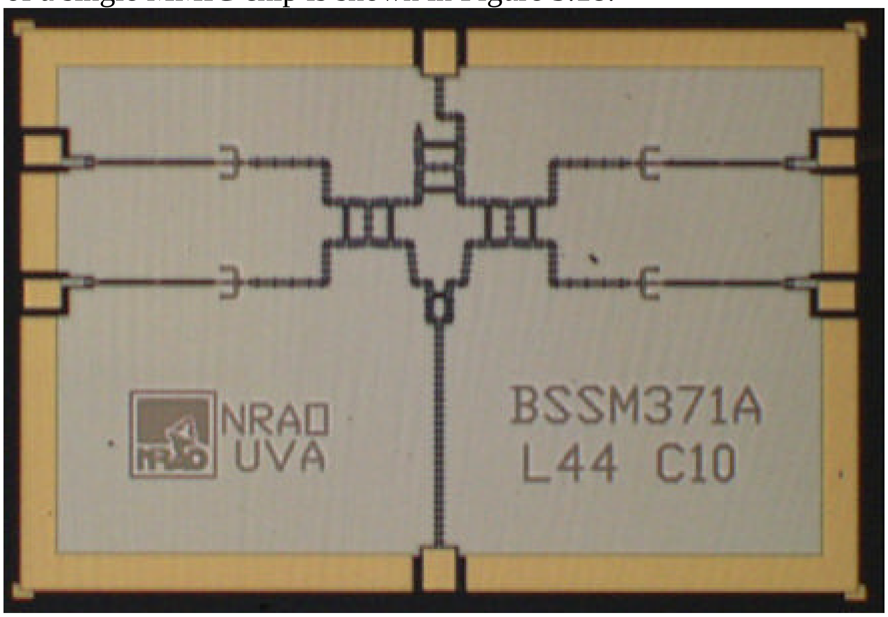


Figure 5.18 - Photograph of a balanced, sideband-separating SIS mixer chip.

5.6.3.3.5 Balanced sideband-separating balanced mixers in waveguide hybrids

An alternate means of achieving balanced, sideband-separating, and balanced sideband-separating operation with SIS mixers is by the use of waveguide hybrids and power splitters with two or four simple DSB mixer chips. The waveguide components can all be machined into a single split-block which also serves as the SIS mixer block. An example of this approach appears in ALMA Memo 316. We have designed and tested such waveguide hybrids in WR-10 waveguide (the highest band for which band we have a vector network analyzer). Figure 5.19 and Figure 5.20 show the computed and measured results for an experimental WR-10 quadrature hybrid. The performance of these experimental structures is satisfactory for use in ALMA receivers, and the required tolerances appear achievable with modern CNC machining techniques for all bands except, possibly, band 10 (787-950 GHz).

This configuration may be preferable to the single-chip balanced sideband-separating mixers in the following circumstances:

1. at the lowest SIS mixer band, for which a completely integrated chip would be relatively large, so a production wafer would contain only a few mixers;
2. at the highest bands, for which ohmic losses in the niobium transmission lines of a single-chip mixer may be too high;
3. if the yield of junctions of acceptable quality were low, so the chance of obtaining four good component mixers on a single chip was reduced to an unacceptable level.

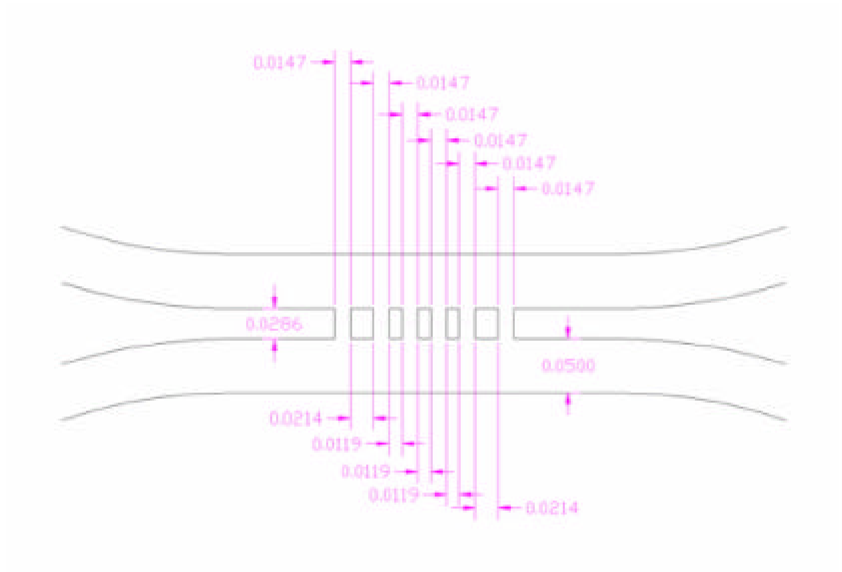


Figure 5.19 - An experimental WR-10 quadrature hybrid.

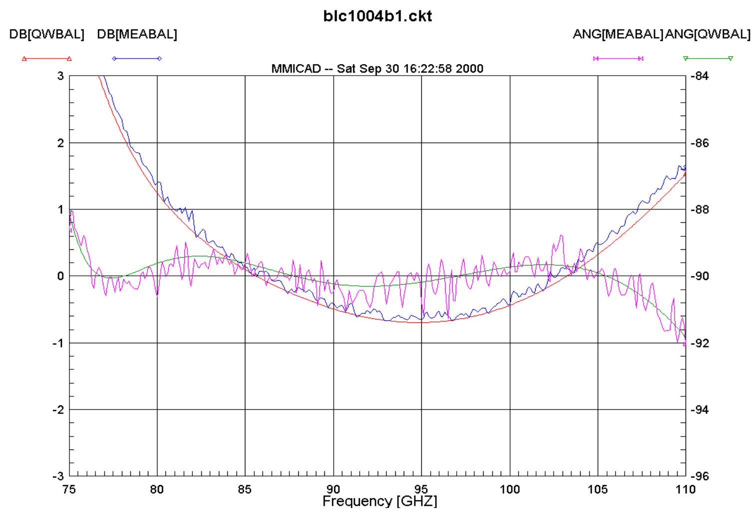


Figure 5.20 - Comparison of a simulation using QuickWave with measured results. The smooth curves are the predictions, and the noisy curves are measured data.

In order to achieve the 8 Ghz bandwidth needed to satisfy the ALMA specifications new techniques are required. One option is to integrate the IF amplifier into the mixer. Work carried out at the CDL in this regard is described below.

5.6.4 Integrated IF Amplifier

Last revised on November, 05 – 2000 by Eugene Lauria, A.R. Kerr, S.-K. Pan, J.C. Webber.

Revision History: 2000-10-05: Revised from 1999 MMA version for ALMA.

5.6.4.1 Introduction

Two options were considered for the 8-GHz-wide IF in the 211-275 GHz SIS receivers for ALMA. The conventional approach uses an IF isolator between the mixer and IF amplifier, while a new scheme, based on earlier work done at OVRO in collaboration with the NRAO, uses an IF amplifier stage inside the SIS mixer block and no isolator. The latter scheme allows an IF covering more than an octave, chosen as 4-12 GHz. The need for an isolator in the conventional scheme would force the IF center frequency to at least 12 GHz (IF = 8-16 GHz) to achieve an 8 GHz bandwidth, probably with a significant noise penalty. The penalty is not simply a result of the increase in amplifier noise temperature at the higher frequency, but includes the noise from the cold termination of the isolator which is reflected from the mixer output.

The use of a high intermediate frequency, as required by both the above schemes, imposes a constraint on the output capacitance and inductance of the SIS mixer. In most SIS mixers, the RF tuning circuit adds substantial IF capacitance in parallel with the SIS junction. We have developed an SIS mixer with low IF capacitance, and this design was used as a building block in the sideband separating and balanced mixers described in section 5.6.3.3.4.

5.6.4.2 Development

In collaboration with M. Pospieszalski of the NRAO Central Development Laboratory, we have developed and interfaced to a 211-275 GHz SIS mixer a 3-stage IF amplifier covering 4-12 GHz (Figure 5.21). This amplifier uses discrete InP HFET transistors to achieve minimum noise and power dissipation, a critical factor in maintaining the SIS junctions at the lowest possible temperature. Due to the high f_T of InP devices, the frequency dependence of their noise parameters is much lower than that of GaAs devices. This is important in order to obtain low noise over broad bandwidths.

Initially, the IF amplifier was optimized for minimum noise with a 50 ohm input load impedance. The SIS mixer is connected to the IF amplifier with a single bond wire and requires no additional matching circuitry. In this particular case, further optimization of the input circuit does not yield any substantial improvement in noise performance over the existing network used for the amplifier by itself. Although this matching network happens to work in this case, it may not work for other mixers. Having the input matching circuit optimized for an input load impedance of 50 ohms makes it handy for testing the amplifier because the mixer block and a type-K connector can be interchanged. To minimize parasitic reactance between the mixer and amplifier, the bias circuit for the mixer is incorporated in the existing amplifier block. This has the added advantage that the amplifier and the mixer bias circuit are tested together which reveals any undesirable interaction between them.

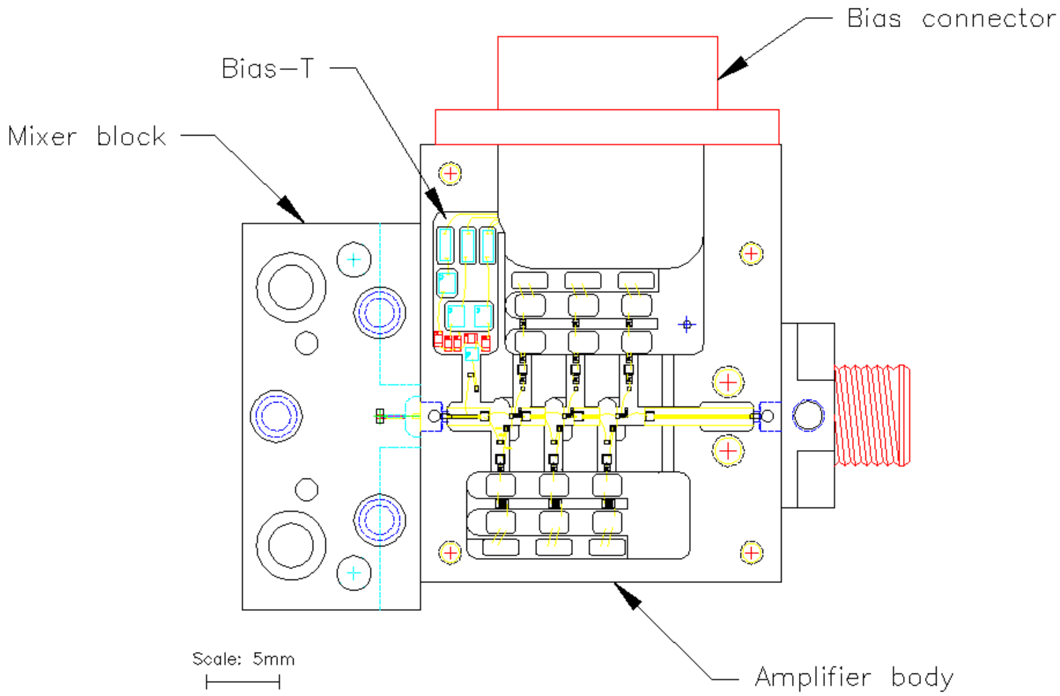


Figure 5.21 - Physical layout of the experimental integrated mixer/amplifier.

Initial experiments have been carried out with a single-ended building-block mixer. The results are shown in Figure 5.22 and Figure 5.23. The performance with the 4-12 GHz IF as a function of RF frequency is essentially the same as for the 1.5-GHz IF chain.

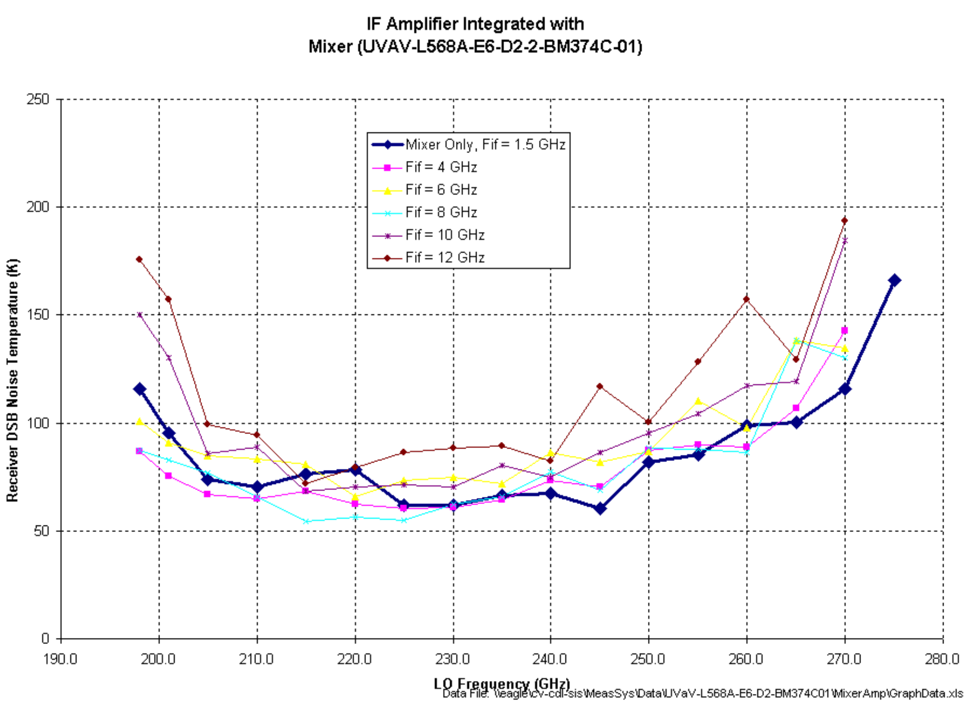


Figure 5.22 - Initial results for a SIS mixer with the experimental IF amplifier, as a function of LO frequency.

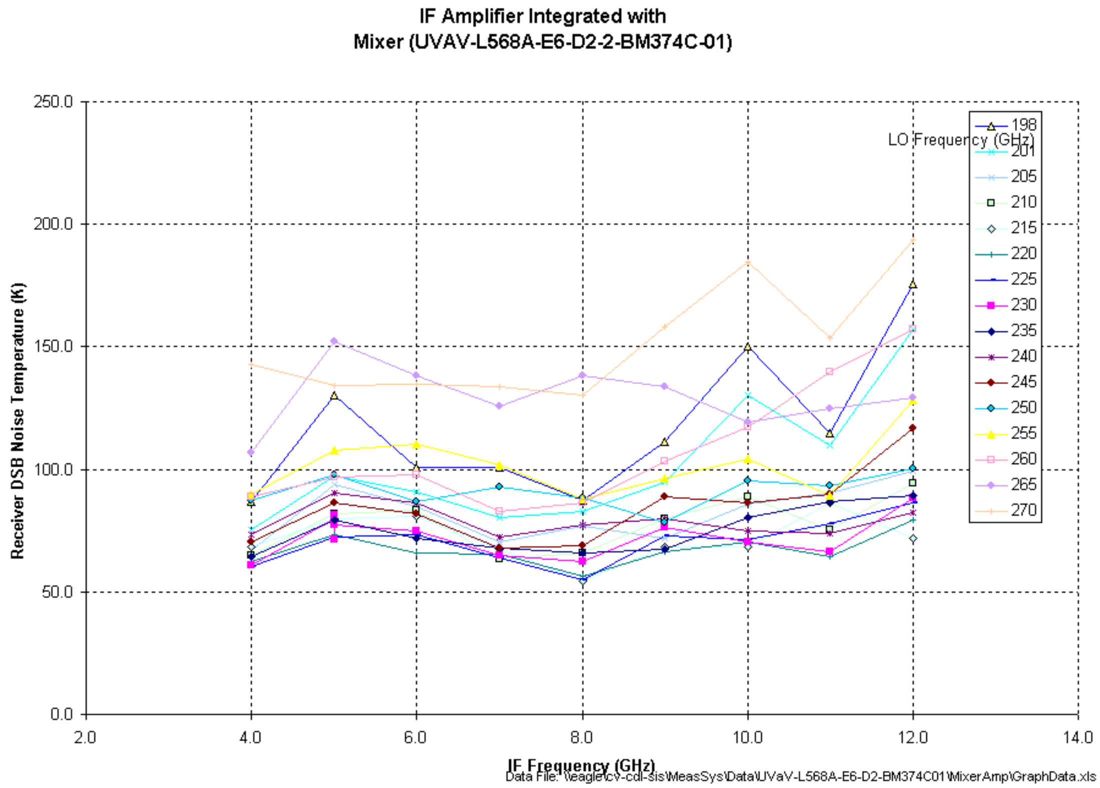


Figure 5.23 - Initial results for the experimental integrated SIS mixer/wideband IF amplifier, as a function of intermediate frequency.

5.6.4.3 Further plans

The next step will be to try different mixers to see how they interact with the amplifier. There may be some cases in which the amplifier will see a negative input load impedance from the mixer. It is not certain how the amplifier will perform if it sees such an impedance. Also, integration of a balanced image-separating sideband mixer will be undertaken. In this configuration, the amplifier input circuit has to allow for two bias-T's for the biasing the two building block mixer junctions of each balanced mixer. Since there are two balanced mixers (four junctions), two amplifiers will be required. The output of these two amplifiers will be combined by a quadrature hybrid which separates the upper and lower sidebands across the IF band.

5.6.5 Band 7 Mixer Development at Onsala Space Observatory, Chalmers University

Last revised on November 23, 2000 by V. Belitsky

<u>Revision history:</u> 2000-10-30: New

5.6.5.1 Introduction

A baseline for *ALMA Band 7 SIS mixer design*, proposed by Onsala Space Observatory, is a sideband separation mixer using quadrature scheme with two identical DSB SIS mixers pumped by a local oscillator (LO) with 90° phase difference. This technology at short mm-waves was pioneered by NRAO and demonstrated at 200-280 GHz band [1]. The main advantage of the sideband separation scheme is that no further tuning is required to provide single side band (SSB) operation compare to other schemes even though fixed-tuned DSB mixers are used. The upper (USB) and the lower sidebands (LSB) are available simultaneously at the two mixer outputs and this relaxes the ALMA requirement of having 8 GHz IF frequency band by a polarization channel, allowing to use a sum of USB and LSB with 4 to 8 GHz IF band for each SIS mixer. The description below outlines the suggested design of the mixer for one polarization channel with assumption of having identical mixer for the second polarization channel.

The block-diagram of a quadrature sideband separation mixer is presented in Figure 5.24: the input RF signal is divided and distributed between the two identical DSB mixers, the LO power is also divided and coupled to the mixers with 90° phase difference. The IF outputs of the two mixers are connected to an IF quadrature hybrid, thus the down-converted USB and LSB signals appear separately at the two output ports of the hybrid.

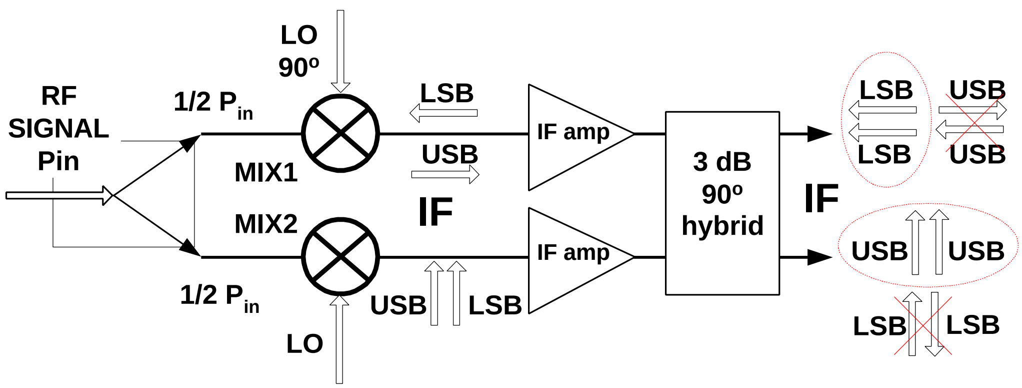


Figure 5.24 - Layout of the sideband separation mixer. The crossed out items at the hybrid outputs are the rejected sidebands (180° phase difference). LSB and USB stand for low and upper side band respectively.

5.6.5.2 Mixer Block Layout

In the present design we take advantage of a new device, a *double-probe coupler* structure that splits the input RF signal between the two ports, apparently, with minimum losses over a wide frequency band and provides transition from a waveguide to a microstrip line for easy integration of the SIS mixers [2]. In that design the SIS mixers are integrated on the same substrate as the double-probe structure. The layout of the mixer, corresponding to the block-diagram in the Figure 1 and employing the double-probe coupler is presented in the Figure 5.25. It is possible to use the spilt-block technique and CNC machine for the mixer block fabrication, which would ease mass fabrication; both mixers are located on the same substrate providing a high degree of *similarity* in the SIS junction performance and the geometry of all the mixer elements including the transmition lines. Balance between the two mixers is extremely important to keep symmetric phase and amplitude for the signal and LO and achieve required image band rejection (>10 dB) [3].

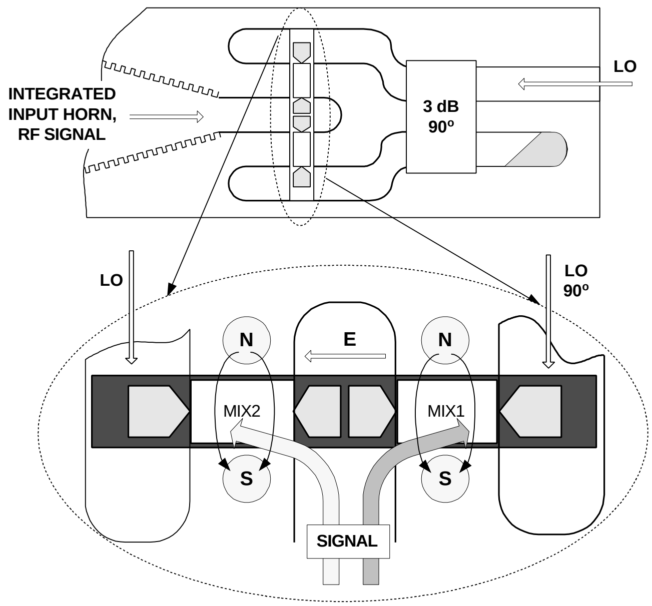


Figure 5.25 - *On the top:* The layout of the sideband separation mixer employing the double-probe coupler; *on the bottom:* the substrate with the two-probe coupler, the two SIS mixers and the single-probe LO injecting feeds.

5.6.5.3 Mixer Chip Layout

The substrate penetrates the three waveguides; the middle waveguide is coupled to the integrated corrugated horn. The two outer waveguides bring the LO signal from the outputs of the 3-dB, 90^{o} branch-line waveguide coupler of a similar type as in [4]. On the chip we place the two mixers with their respective tuning circuits and LO injection coupler with local oscillator guiding circuitry. Figure 5.26 shows schematically layout of the mixer chip.

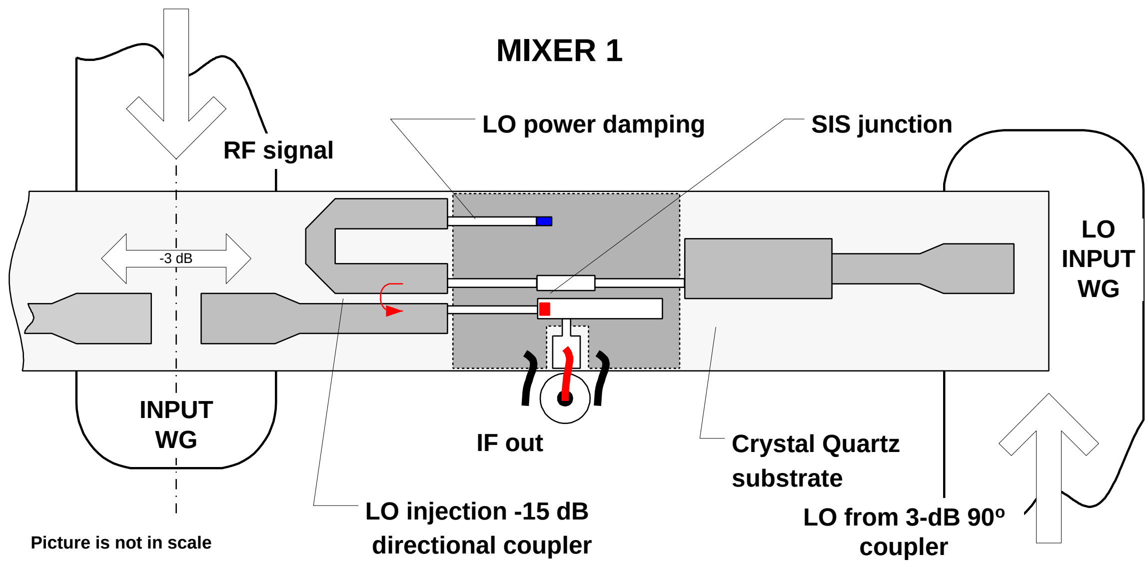


Figure 5.26 - Mixer chip layout: the figure covers area around *Mixer 1* (as in Figure 5.25). SIS mixer tuning circuit consists of an inductive section followed by an open quarter-wave stub. A quarter-wave transformer is coupled from another side for matching of the tuned mixer to the double probe structure connected through the LO injection quarter-wave coupler. All shown lines are microstrip type transmition lines.

5.6.5.4 Mixer Interfaces

5.6.5.4.1 Optics

At the moment of writing these notes the ALMA optical design is still in the discussion stage and no optical interfaces for cartridges have been defined. The cartridge design is pending readiness of the main receiver optics design.

The mixer described above will be fabricated using split-block technique and employing CNC milling machine. Depending on complexity requirements by the optical interface we plan to integrate the scalar horn into the mixer block (fast beam) as it is depicted in Figure 5.25. Alternatively, if the horn should be long (slow beam required) we will use a standard waveguide flange connection between the mixer and the horn.

5.6.5.4.2 LO Feed and LO Power

The LO power required for one polarization channel was calculated as follows: we included in the model 2 SIS junctions (R_n=5 Ω, A=5 μm^2), –15 dB for the LO injection via the coupler, frequency dependent loss in the transmition lines on the substrate and waveguides, 2 dB ripple in both couplers (on the substrate and WG 3-dB coupler) and margin 3 dB. Calculations of the LO power are made following model suggested in ALMA MEMO 264; additionally we added a provisional dependence of the SIS power coupling with RF integrated tuning.

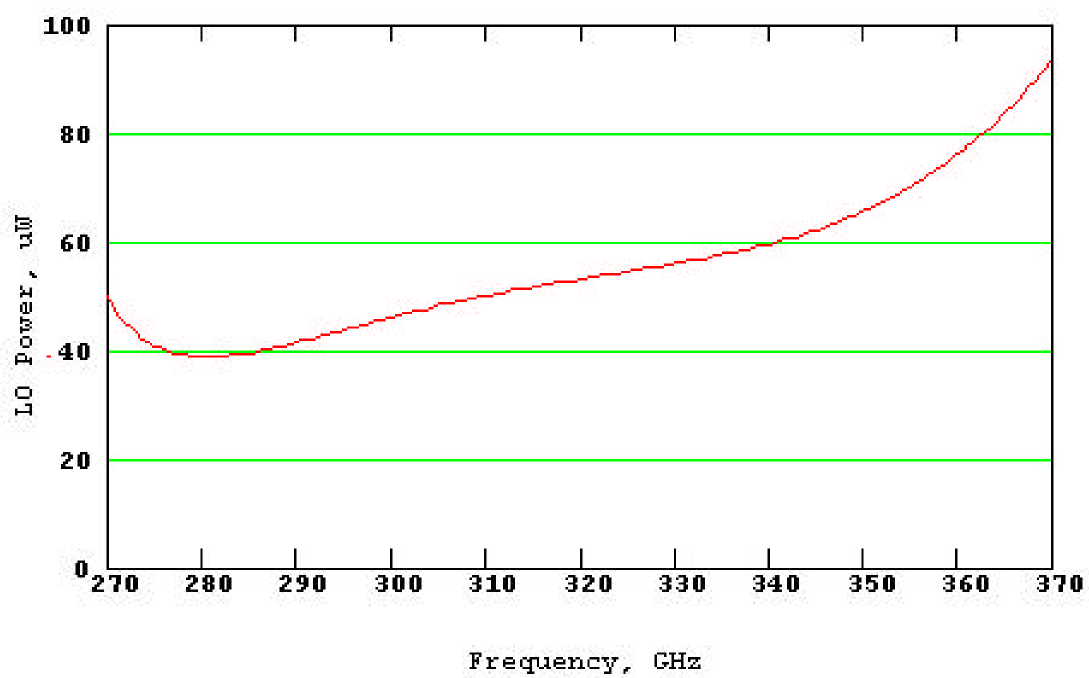


Figure 5.27 - LO power required by the sideband-separating mixer for one polarization channel.

For the mixer described here the LO interface would be just a waveguide feed connected to the input of the integrated 3-dB 90^o coupler as in Figure 5.25. The two mixers fabricated on the same substrate are matched with respect to the required LO and we do not consider at the moment any individual LO level adjustment inside the mixer. We expect though that the LO distribution circuitry for different polarizations will have a ***balance attenuator*** to allow different level of LO power between the polarization channels (LO injection scheme pending finalizing of the optical interfaces and the cartridge design). As a result, the total power for the two-polarization system would be somewhat more than 2 times higher (insertion loss) than the one depicted in Figure 5.27 .

5.6.5.4.3 Intermediate Frequency

The mixer will use two cryogenic IF amplifiers connected to the mixers with isolator and coupled to 3-dB 90-degree coupler at the output. IF block diagram is shown in Figure 5.24. ALMA IF band is 4 – 8 GHz and two options for IF amplifiers are considered: ***i.*** integrated amplifier with direct connection to the SIS mixers (no isolators, bias tee integrated into the first stage of the amplifier); ***ii.*** IF amplifier based on discrete components with an isolator at the input. The first option is under development at NRAO, Charlottesville. Onsala group, in collaboration with Microwave Technology Dept., Chalmers University, works on the developing of a low-noise cryogenic amplifier based on GaAs HEMT transistors for 4 – 8 GHz band (later plan to go for InP HEMT). The amplifiers should be matched in phase and gain to achieve required sideband rejection. Onsala design considers built-in adjustment of the amplifier gain to equalize overall gain (including mixers) in both channels of the mixer.

5.6.5.4.4 DC Bias, Magnetic Field, Heater and Temperature

DC bias uses circuit with a shunt resistor. The circuit similar to the presented in Figure 5.28 is in use at Onsala SIS mixers (and many other places) and has a number of advantages, including protection against static discharges (SIS junction is always connected to the ground via the shunt resistor (2 resistors of 10 W in series in our case).

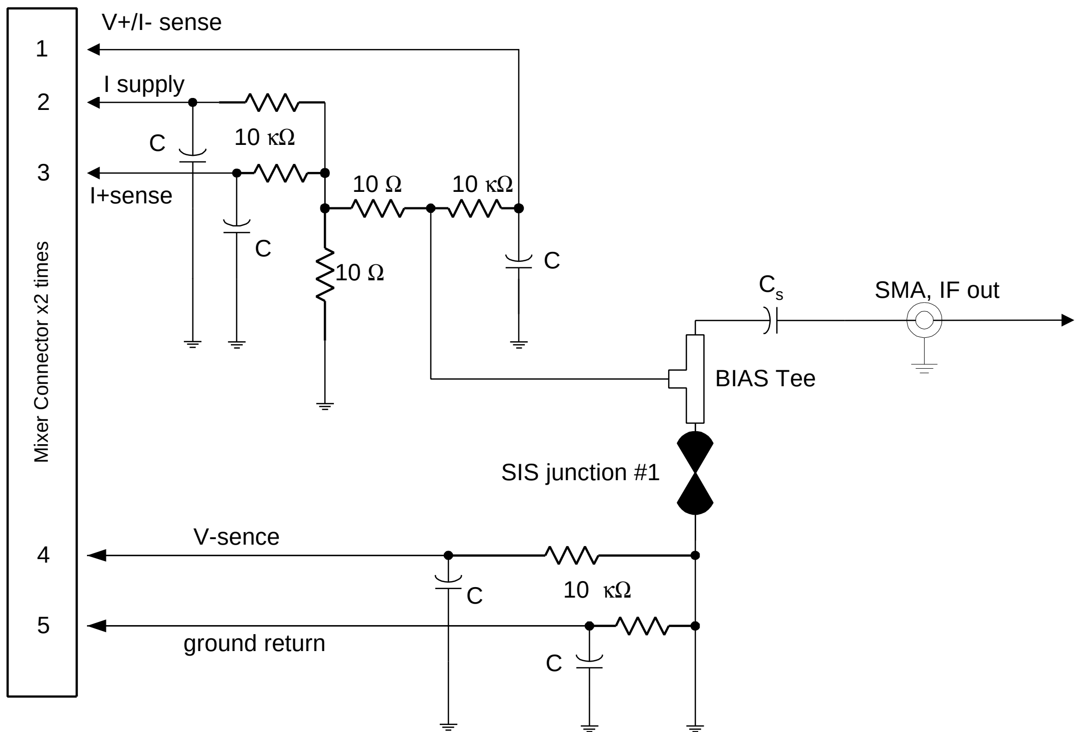


Figure 5.28 - DC bias circuit diagram with 10 W shunt resistor. Normally, all the shown components, chip resistors and capacitors, are integrated into the mixer block. Depending on the type of IF amplifier used, the bias tee would be integrated into the amplifier instead.

Both passive bias voltage stabilization (stable voltage between the contacts #2 and #5 as in Figure 5.28) and active voltage/current source with feedback are possible to use with the circuitry above. To avoid problem with ground loops we suggest using floating DC bias with the only grounding point at SIS junction mounting in the mixer block (separate ground return). Each of the two SIS junctions will require 5 wires for DC bias, total 10 wires.

Magnetic field to suppress Josephson current will be generated by the two separate coils dedicated for each of the two SIS junctions (Figure 5.25 shows position of magnetic poles around the two SIS mixers). We plan to use magnetic field guiding (high μ metal) to minimize required currents. The coils should be fed by a separate driving electronics (current stabilization, two-wire circuitry) to provide individual tuning for the two SIS mixers, preferably with floating power supply to avoid ground loop problem. Magnetic field will require in total 4 wires.
In order to better control Josephson current via applying of the magnetic field we need also control over magnetic fields while the system is cooling down and possibly “frozen-in” or trapped fluxes of the magnetic field could be a potential problem. The fluxes may also appear as a result of abrupt change of the DC bias current or using electro powered instruments nearby the

receiver. Temporary warming up of the mixer above the temperature of the superconducting transition, $T_c \sim 9.2$ K for Nb film would allow us to remove the frozen fluxes. We suggest including a heater for each mixer to control frozen fluxes and simplify suppression of the Josephson current. The two-wire circuitry with current stabilization, floating power supply, total 2 wires per mixer block.

Mixer ambient temperature information is very essential for understanding and solving possible problems during SIS mixer operation. We suggest installation of a temperature sensor on every mixer block. If the IF amplifiers employing circulators would be used, we suggest to monitor the temperature of the termination load installed on the circulators. Standard Lake-Shore temperature sensors or simular, 2 wires per sensor.

5.6.5.5 References

[1] A. R. Kerr, S.-K. Pan and H. G. LeDuc, "*An integrated sideband separating SIS mixer for 200-280 GHz*", Proc. of the Ninth Space Terahertz Technology Symposium, Pasadena, USA, March, 1998.

[2] V. Vassilev, V. Belitsky and R. Booth, "*A New Sideband Separation SIS Mixer for ALMA*" Proc. of SPIE, volume 4015, March 2000. Can be obtained via http://gard04.mc2.chalmers.se/papers/SPIE_2000.pdf

[3] A. R. Kerr, S.-K. Pan, A. W. Lichtenberger, N. Horner, J. E. Effland, and K. Crady, "A Single-Chip Balanced SIS Mixer For 200-300 GHz ", ALMA Memo Series, *Memo 308*, http://www.mma.nrao.edu/memos/html-memos/abstracts/abs308.html

[4] S. M. X. Claude, C. T. Cunningham, A. R. Kerr, and S.-K. Pan "*Design of a Sideband-Separating Balanced SIS Mixer Based on Waveguide Hybrids*", ALMA Memo Series, *Memo 316*, http://www.alma.nrao.edu/memos/html-memos/abstracts/abs316.html

5.6.6 Band 7 Mixer and Cartridge Development at IRAM

Last revised on 27 Nov 2000 by S. Claude, IRAM

<u>Revision history:</u> 2000-11-23 first version

5.6.6.1 Summary

We describe here IRAM's development for the realisation of Band 7 cartridge. Our baseline design involves two DSB mixers for each orthogonal polarization with waveguide couplers LO injection. The polarizations are separated by one grid. The 17 dB crossguide coupler allows LO injection in a compact configuration. The mixers to be used in the cartridge are DSB, fixed tuned across the RF frequency range (275-370 GHz) and low noise for an IF covering 4 to 8 GHz. Future development involves integrated sideband separation mixers in waveguide.

5.6.6.2 Cartridge layout and optics

The cartridge contains three cold plates, one at 4K for the mixers, mirrors and grid, one at 15 K for the IF LNA and one at 70 K for the input LO multiplier. The baseline system involves two orthogonal polarizations with two DSB (double side band) single-ended mixers. Fig. 1 shows the layout of the components in the cartridge with the input optics.

A more precise description of the optics layout will be given in the chapter on the receiver optics, and we give here only a brief description (Fig. 2). The telescope beam waist is at the cryostat top plate, which is situated 130mm off the cryostat axis. The beam enters into the cryostat and is reflected at an angle of 116° on to an elliptical mirror. A reflection of 26º gives an intermediary waist of 2.4mm, where a compact polarization grid is placed. The two orthogonal polarizations are then directed onto two elliptical mirrors of reflection angle of 26º and then reflected onto flat mirrors into the corrugated feed horns.

The reasons for the added complexity of the optics were to ease the layout for the mixers and the local oscillator injection. Moreover, the low angles of reflections on the input elliptical mirror will reduce any crosspolar. With this scheme we have two signals of orthogonal polarizations coming into parallel waveguide paths of the same orientation, which allows a series of upgrades for the mixers without modification of the optics.

The LO is injected in both mixers from a multiplier on the 70 K stage via two crossguide couplers in series. A magnetic coil is attached to each mixer to suppress the Josephson current. Finally the output IF signals are amplified by cooled HEMT amplifiers at 15 K.

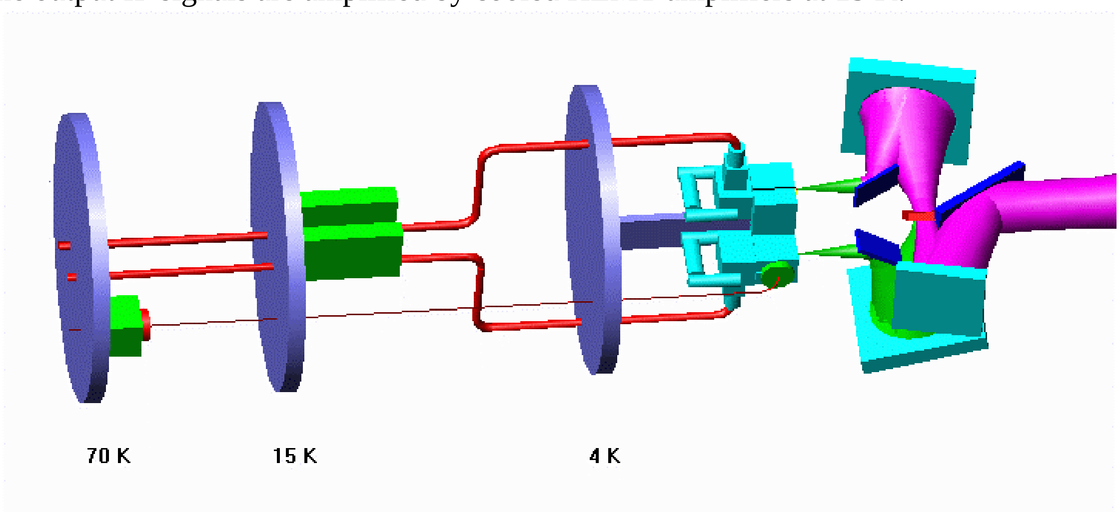


Figure 5.29 - Layout of the main components in the cartridge

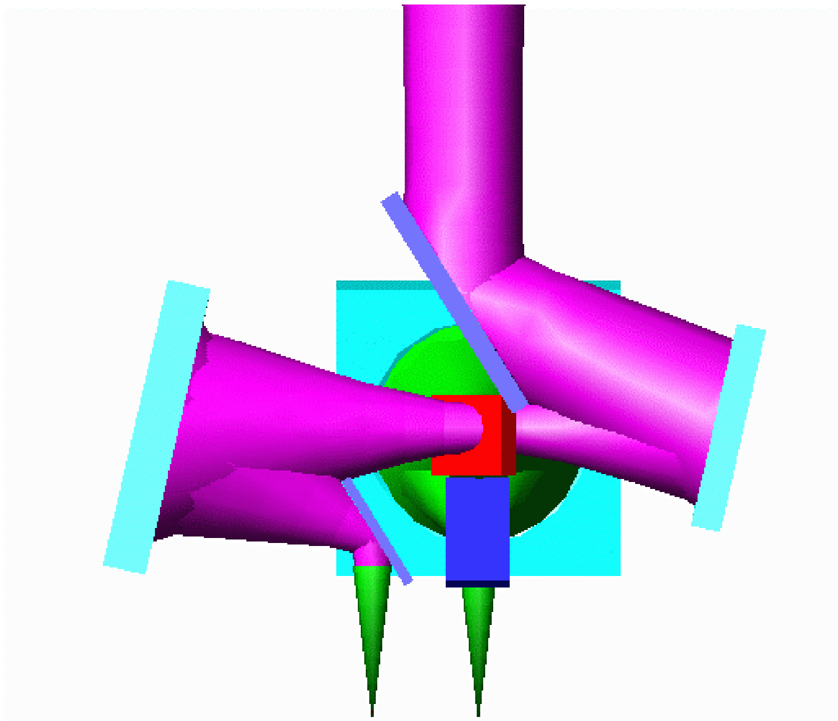


Figure 5.30 - Close up view of the optics

5.6.6.3 Component development

5.6.6.3.1 LO injection: a compact crossguide coupler

A compact crossed guide coupler for the frequency range of 275 to 370 GHz has been developed for the injection of the LO signal. The design is shown in Fig. 3.

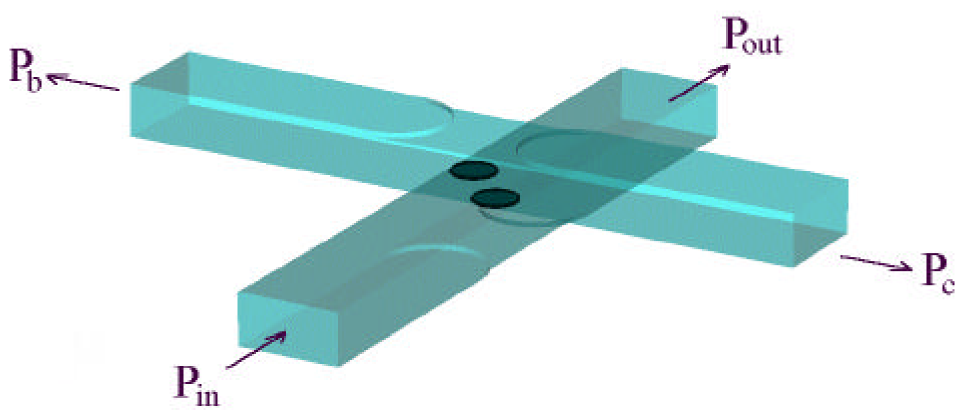


Figure 5.31 - Schematic view of the crossed guide coupler with Pc and Pb corresponding to forward coupled power and backward coupled power, respectively.

Coupling is achieved via two round holes. Simulations carried out with an electromagnetic simulation software (CST Microwave studio) indicates that this simple type of coupler achieves a coupling around 16 dB varying only by 1 dB over the whole frequency range and a directivity of about 10 dB.
Since the performance of our VNA is better in the frequency band around 230 GHz, the design was scaled down to this frequency range for the fabrication of a prototype. Results of simulation and measurements of this prototype are shown in Fig. 4. The directivity is not very good, but that should not be a problem since the input match of the mixer is not expected to be very good.

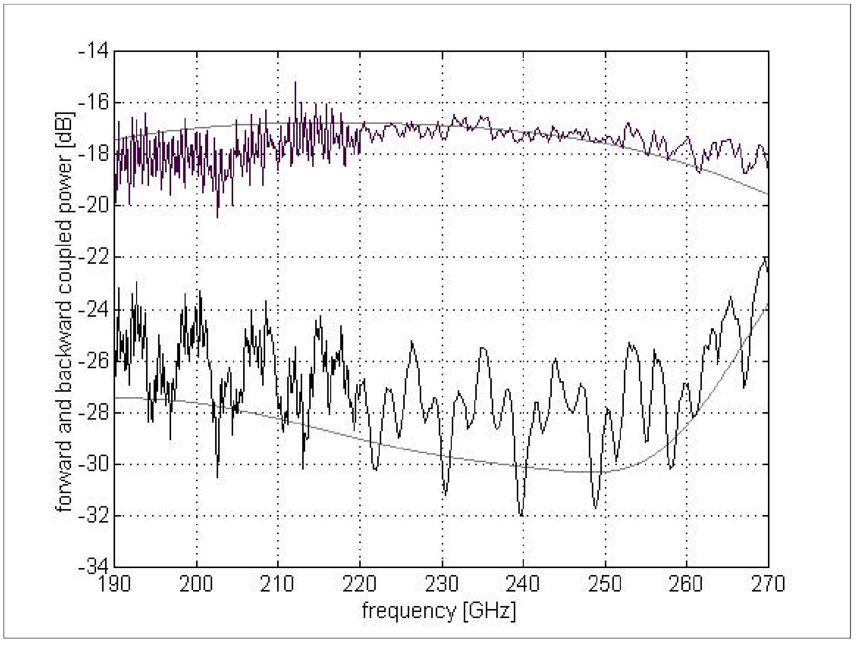


Figure 5.32 - Simulation and measurements of the crossed guide coupler, scaled to band 6

5.6.6.3.2 Mixer baseline design

A full height waveguide SIS mixer covering the 275-370 GHz frequency band has been designed. The fixed tuned single junction Nb/Al-AlOx/Al mixer will operate in Double Side Band. A ~30 % operating bandwidth can be achieved by using an "end-loaded" tuning stub to tune out the junction capacitance of 75 fF (junction size 1 µm2) followed by two quarter-wave transformer sections. All the transmission lines integrated in the mixer chip are implemented in superconducting microstrip with the exception of a section of the quarter-wave transformer, which is realized as a Capacitively Loaded Coplanar Waveguide (CLCPW). The junction is mounted on an 80 µm thick quartz that stretches only part way across the waveguide. Fig. 5 shows a three-dimensional view of the mixer including the full height waveguide to suspended microstrip transition, the low pass "hammer" type filter and the antenna probe.

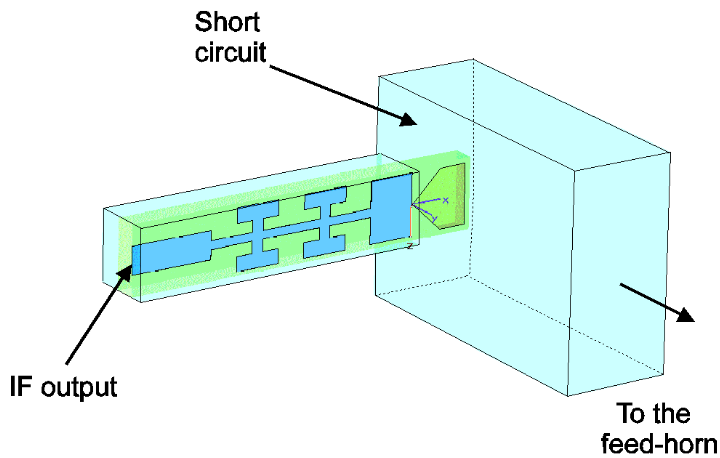


Figure 5.33 - View of the mixer substrate and the input waveguide

A detail of the mixer chip is illustrated in Fig. 6, which includes the SIS junction and its integrated matching structure. In Fig. 7, the simulated results for the embedding impedance seen by the junction are displayed as a function of frequency. The SSB noise temperature of the receiver Trec consisting of the mixer cascaded with a LNA operating at a central IF frequency of 6 GHz (TIF= 6 K is assumed) has been calculated from the complete quantum mechanical treatment. In Fig. 8, the expected value of Trec referred to the mixer input is plotted as a function of IF frequency for three different RF frequencies. SSB receiver noise temperature in the range 23-35 K is expected in the 275-370 GHz frequency band.

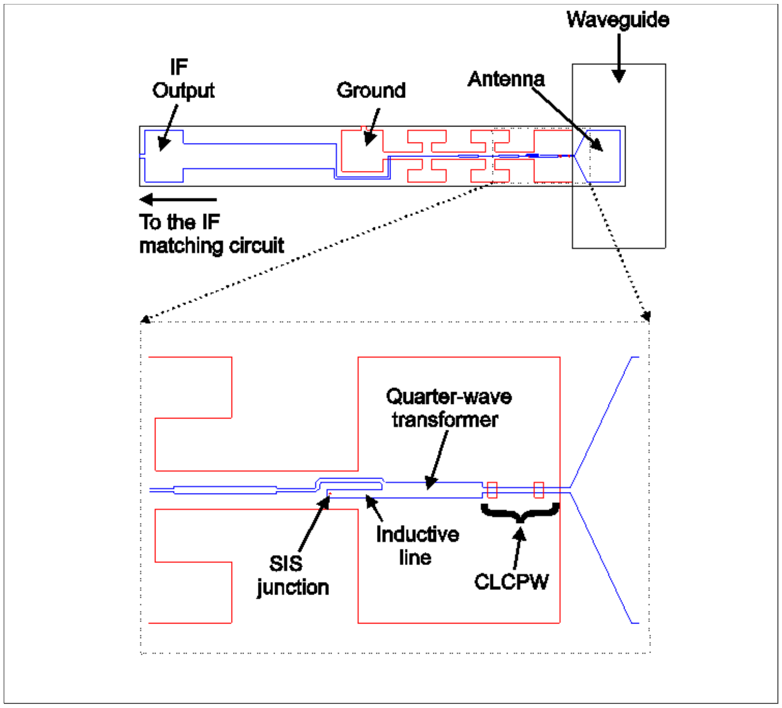


Figure 5.34 - Mixer chip layout

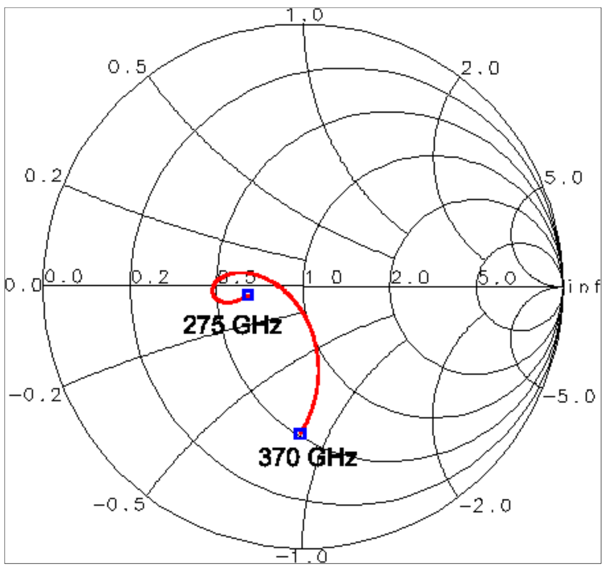


Figure 5.35 - Simulated embedding impedance of the junction in the mixer block, normalized to the RF impedance of the junction (18.7O)

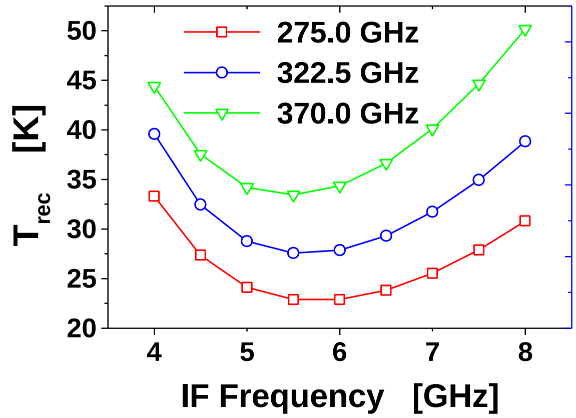


Figure 5.36 - Expected SSB receiver noise temperature referred to the input of the mixer for three RF frequencies, across the IF band.

5.6.6.3.3 Mixer future developments

In parallel with our baseline DSB solution, we are developing a 2SB (sideband-separating) mixer. The mixer integrates an input quadrature hybrid in waveguide, an in-phase LO splitter, 2 cross-guide couplers for the LO injection and 2 single-ended mixers as described in Fig. 9. Provision has been made so that the layout in the cartridge and the input optics would allow the integration of one 2SB mixer for each polarization.

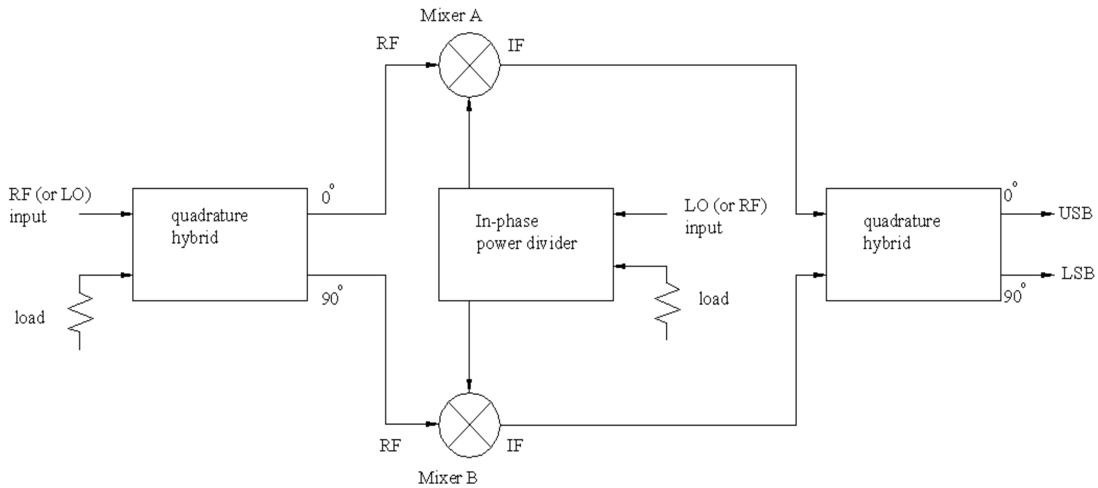
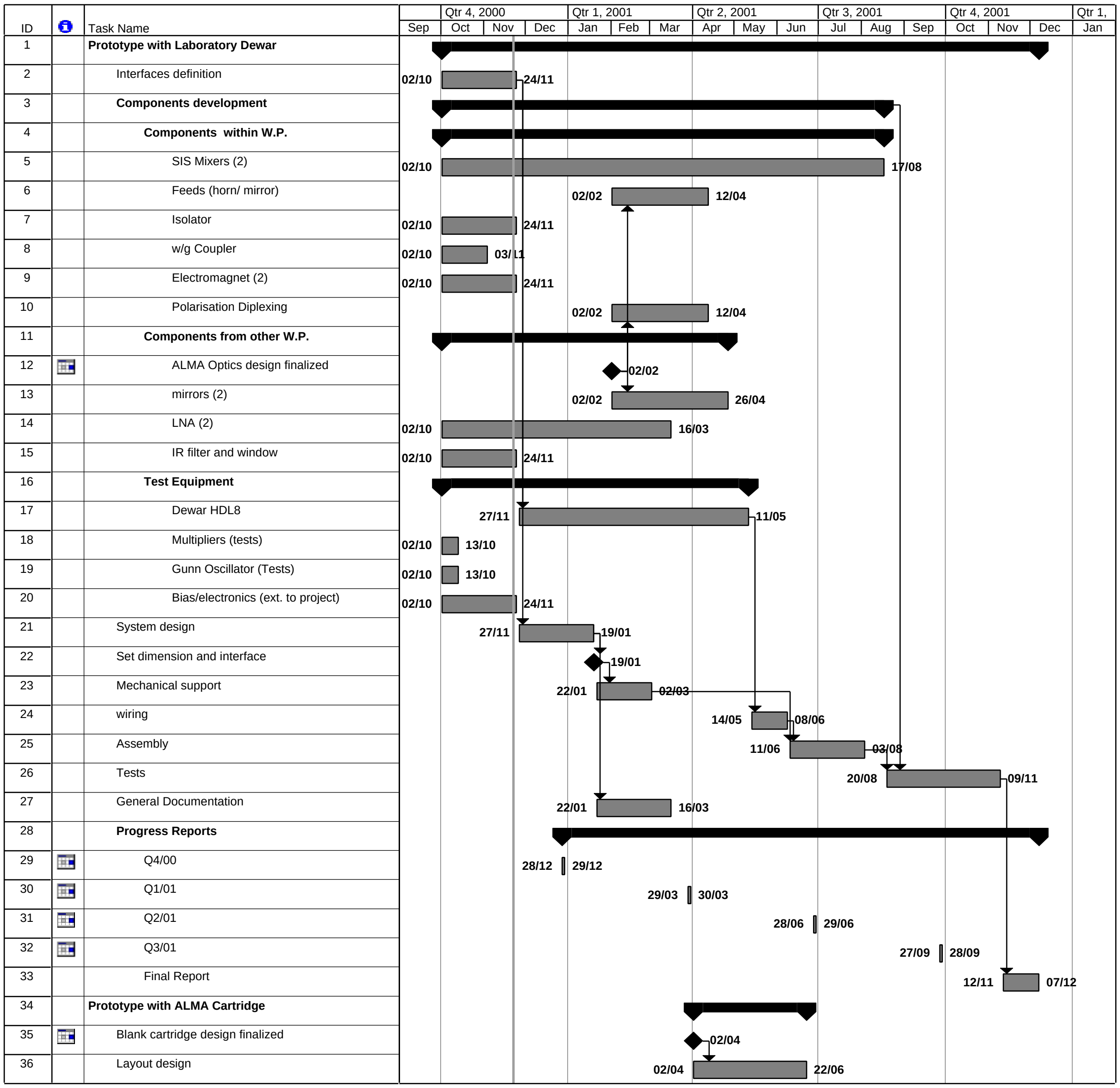


Figure 5.37 - Schematic diagram of the 2SB mixer

5.6.6.4 Timeline



5.6.7 Band 9 SIS mixer development at NOVA/SRON

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Revision History: 2000-11-22: first version

5.6.7.1 Summary

This section describes the SIS mixers for ALMA band 9, 602 to 720 GHz, developed at SRON and funded by NOVA. Starting from a design of a single-ended fixed tuned SIS mixer for the JCMT D-band (625 to 710 GHz) and a quasi-optical SIS mixer for HIFI (800-1050 GHz), we are developing balanced mixers both in waveguide design and quasi-optical design for ALMA band 9. The two quite different design approaches have been chosen in order to assess the advantages and disadvantages of each design in terms of performance, ease and cost of manufacturing and assembly. The goals for the design and development phase are to produce prototypes of each design. The goals for the construction phase are to produce large numbers of mixers of the chosen design with repeatable performance at minimum total expense.

5.6.7.2 SIS Mixer Specifications and Development Schedule

Table 5.7 shows some of the SIS mixer specifications. Although the ALMA front end specifications call for a 8 GHz IF bandwidth, this issue can only be assessed in detail after having available experimental results which prove that this wide IF bandwidth is indeed the best choice for the science to be done with ALMA. The 8 GHz IF bandwidth is scientifically driven by the desire to have maximum continuum sensitivity. However, to ensure this scientific goal, the 8 GHz bandwidth needs to be achieved without increase of receiver noise temperature and without decrease of receiver stability as compared to a lower IF bandwidth.. Intense development work to make an 8 GHz IF integrated amplifier available is being carried out at NRAO. SRON will integrate such an amplifier (produced at NRAO) into the mixer designs for band 9.

Table 5.7 SIS mixer specifications

Item	Specification
Receiver noise temperature	Noise sufficiently low to produce double sideband receiver noise (referred to the vacuum window) of 168 K over 80% of band, 250 K at any frequency
Frequency band covered	Band 9, 602 – 720 GHz
IF bandwidth	8 GHz, falling in band 4-12 GHz
Configuration	Balanced or single ended DSB operation, no mechanical tuners, waveguide or quasi-optical beam coupling

We intend to carry out the first tests of a balanced mixer in April 2001 and integrate the 4 – 12 GHz IF amplifier from NRAO into the mixer by June 2001. A front end CDR is planned for end of 2001.

5.6.7.3 Balanced waveguide SIS mixer

As already mention in Section 5.6.3.3.3 the use of balanced SIS mixers has two potential advantages for ALMA. One is the lower LO power requirement as compared to single-ended mixers (typically –17 dB), the other is the inherent rejection of AM sideband noise accompanying the LO. For the development of a balanced waveguide mixer, we start from a proven design of a single-ended fixed tuned mixer for the 650 GHz band (developed at SRON by H. van de Stadt, H. Schaeffer, J. R. Gao, L. de Jong, and W. Laauwen). Details of this design are given in Section 5.6.7.4.8. The balanced waveguide mixer will use similar end pieces (junction holders) and SIS junctions as the single-ended design, which have demonstrated a large *rf* bandwidth (on the order of 150 GHz) and low noise. These parts will be optimized for the required *rf* bandwidth and receiver noise of ALMA band 9. An advantage of this design is its simplicity and potential suitability for series production.
The balanced waveguide mixer basically consists of a magic-T with two integrated horns (one for the rf coupling and one for the LO coupling) and two junction back pieces. The principle is shown in Figure 5.38. The *rf* signal is coupled in-phase and the LO is coupled in anti-phase to MIXER1 and MIXER2, respectively. The IF output of the two mixers can be combined if the SIS junctions are biased in opposite directions. The magic-T will be fabricated in split block technique. For ease of manufacturing we chose to start with a diagonal feed horn. It is straightforward to change it to a corrugated feed horn since the horn is inserted into the magic-T block. The Magic-T has larger dimensions (and consequently simpler machining) as compared to other hybrid structures for the same band.
A magnetic field which is needed for suppressing the Josephson noise, is supplied to each junction back piece individually. This allows to compensate for a possible spread in production parameters. Figure 5.39 and Figure 5.40 show the basic design. We expect a performance similar or better to the fixed tuned JCMT D-band mixer (see Section 5.6.7.4.8).

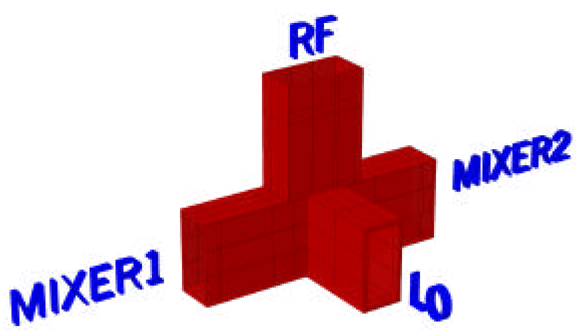

Figure 5.38 - Principle of a magic-T as waveguide hybrid for a balanced mixer.

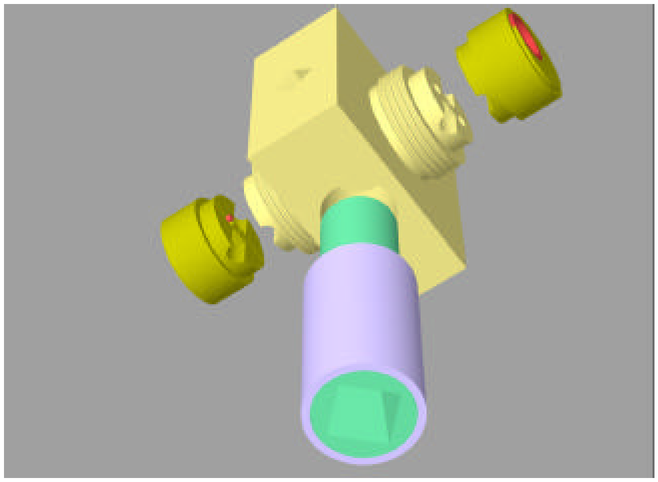

Figure 5.39 - Balanced waveguide mixer design. Clearly visible are the *rf* feed horn (here a diagonal horn) and the LO feed horn on the top of the block. The SIS junctions of the two mixers are mounted in the round end pieces.

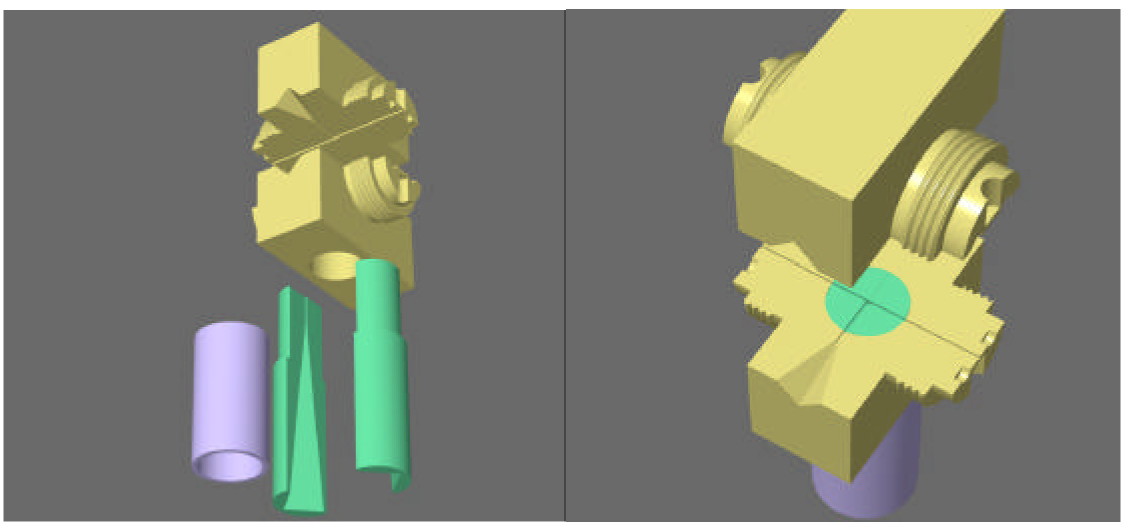

Figure 5.40 - Left: The balanced mixer consists of an inserted horn, magic-T and two end pieces (not shown here). Right: View of the front part of the magic-T with inserted *rf* feed horn and part of the LO feed horn.

5.6.7.4 Quasi-optical balanced SIS mixer

In parallel with the waveguide design, we also develop a quasi-optical SIS mixer for band 9. A quasi-optical mixer has some potential advantages over a waveguide mixer. These mixers are produced with optical lithography which allows to reproduce antenna dimensions with high accuracy. The lens can be produced quickly and in greater quantities (about 200 pcs a day). The estimated cost of the lens is much less than the cost of a corrugated horn for these frequencies. The chip is made of silicon and does not require polishing. The lens can readily produce the beam with an F-number matching the telescope beam without any intermediate optics. In the balanced mixer configuration the LO can be injected in orthogonal polarization with respect to the *rf* signal. That allows to use only one grid for LO injection and polarization separation. Disadvantages of the quasi-optical design include the difficulty to achieve high coupling efficiency to a telescope.

Figure 5.41 shows an example of a quasi-optical mixer basically consisting of the mixer chip with integrated antenna structure mounted on a silicon lens. The lens will have an anti-reflection coating made of Stycast ™ epoxy or Parilen™ C plastic.

Figure 5.41 - Quasi-optical SIS mixer configuration

5.6.7.4.1 General description

The quasi-optical receiver chip will be based on Nb film technology. The losses and additional dispersion that occurs in Nb film above the gap frequency of Nb (~670 GHz) does not allow to use a simplified microstrip line model to be applied for parameter tuning. A full *rf* model including losses in Nb films has been developed during the design. It was found that it is possible to reach good receiver sensitivity at the upper part of the ALMA band 9 (602 – 720 GHz). However, the maximum sensitivity for some design has to be sacrificed in order to get a reasonably flat response across the band.
The *rf* structure of the receiver chip can be divided into four basic elements: the planar antenna, SIS junctions with integrated matching/tuning structure, *dc*/IF leads with IF on-chip transformer and magnetic field control line. The design includes different combinations of antenna structures, number of junctions per mixer, single-ended or balanced configuration and existence of control lines.

5.6.7.4.2 Antenna types

In our design two types of planar antennas are used, the double slot line antenna (DSA) and cross-slot antenna (CSA), Figure 5.42. The DSA is the most commonly used two-port antenna and the CSA is an experimental four-port antenna to be used in connection with the balanced on-chip mixer. The dimensions of the antennas are chosen to give an optimal far-field beam pattern of lens-antenna combination.
Four mixers can be connected to the CSA as shown in Figure 5.42. If the LO and *rf* signals are applied in the indicated polarizations, then the LO and rf signals appear in-phase for mixers M3, M4 and in anti-phase for mixer M1, M2. This symmetry with the proper combination of mixer IF outputs allows to use this configuration as balanced mixer.

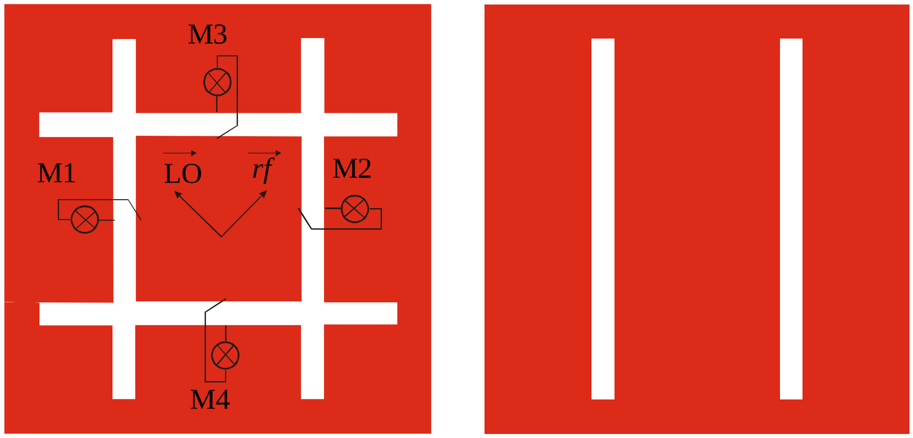

Figure 5.42 - Cross-slot antenna (left) and double slot line antenna (right). The cross-slot antenna in combination with four SIS mixers can be used as a balanced mixer.

5.6.7.4.3 Design types and *rf* properties

Nine design types are included in the mask set for the quasi-optical SIS mixer and are summarized in Table 5.8. The first four types represent a quasi-optical balanced configuration. Each of the four ports of the antenna is connected to a separate junction/tuning circuit. Depending on the polarization of the LO and interconnection of the IF output signals this type of receiver can be used as **double polarization** or **balanced** receiver. Type 5 represents a classical design that was developed also for 950 GHz at SRON. Each design type is reproduced on the mask at least 6 times. The calculated frequency response for types 1 and 2 is shown in Figure 5.43. It represents the *rf* power match from the antenna to the junction. The typical IF transient properties are shown in Figure 5.44. The additional IF tuning element improves the response in the range 2 to 12 GHz.

Table 5.8 – Quasi-optical mixer design types summary

Design type	Tuning structure	Antenna	Control line	Comments
Type-1	Single junction	Cross-slot	No	Balanced mixer
Type-2	Single junction	Cross-slot	Yes	Balanced mixer with control line
Type-3	Twin junction	Cross-slot	No	Balanced mixer
Type-4	Twin junction	Cross-slot	Yes	Balanced mixer with control line
Type-5	Virtual ground	Double-slot	No	End-point mixer (classical design)
Type-6	Single junction	Double-slot	No	End-point mixer (reference for type-1)
Type-7	Single	Double-slot	Yes	End-point mixer (reference

	junction			for type-2)
Type-8	Twin junction	Double-slot	No	End-point mixer (reference for type-3)
Type-9	Twin junction	Double-slot	Yes	End-point mixer (reference for type-4)

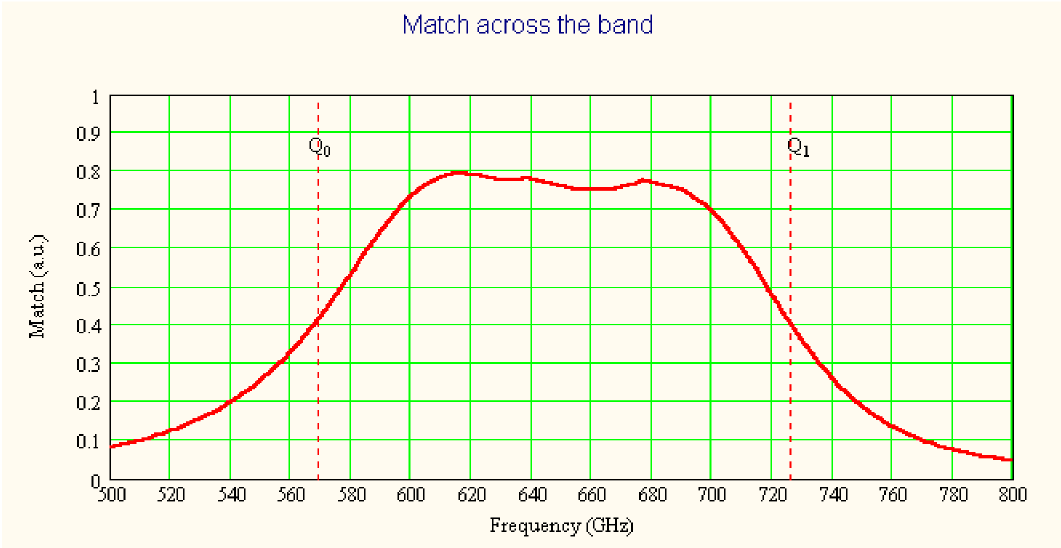

Figure 5.43 – Calculated frequency response of quasi-optical mixer types 1 and 2 (see Table 5.8).

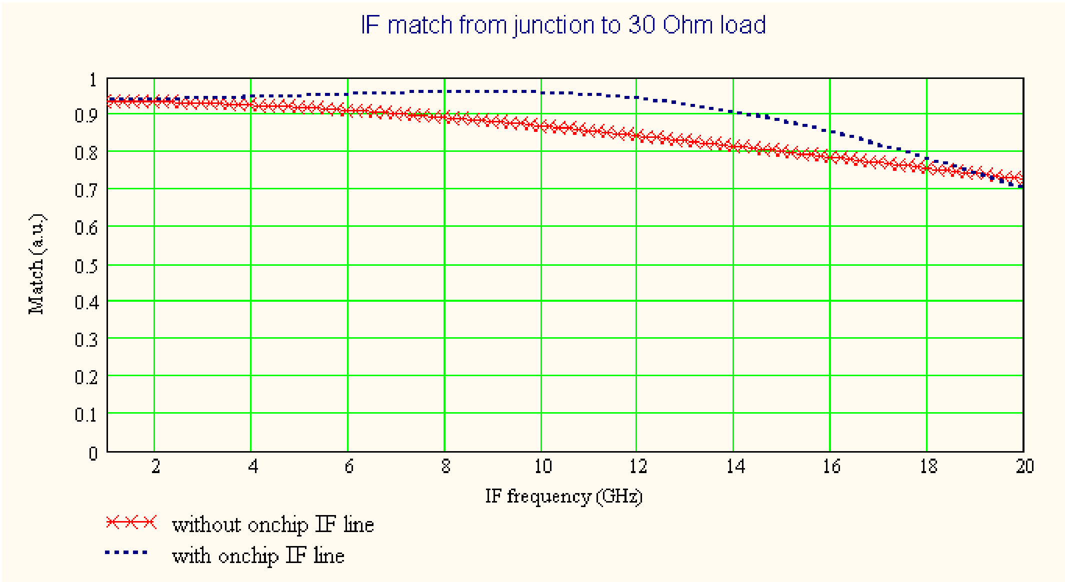

Figure 5.44 – Calculated IF frequency response of mixer types 3 and 4.

5.6.7.4.4 Mask layout

The 2" mask working area is divided into 177 3 x 3 mm square sections. Each section represents a different chip. Four places are used for alignment markers. The total amount of receiver chips is **173**. Each mask plate contains the mask set name “SIS-16” and its individual number 0…4. The ground layers of all chips are connected with each other and with the large contact pad at the edge of the wafer by means of an anodization grid. Each chip is marked with an individual number as well as with its type marker.

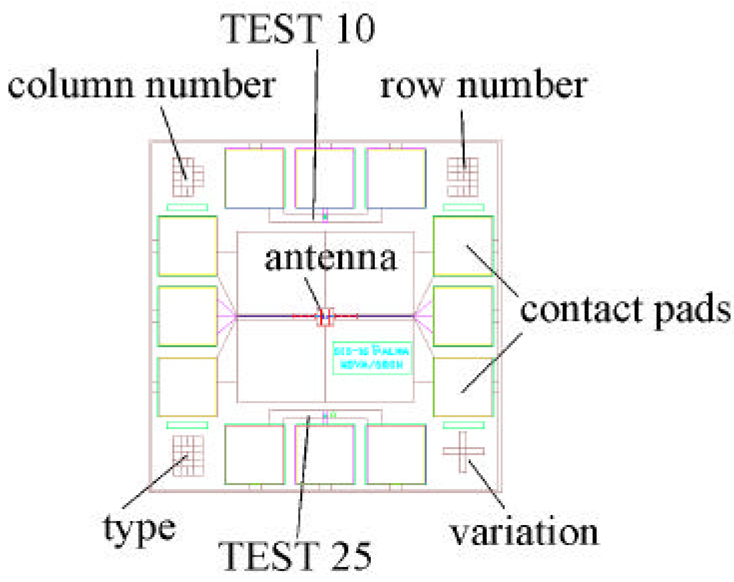

Figure 5.45 - Device chip layout

The SIS16 chip layout is presented in Figure 5.45. The antenna is situated in the center of the chip. The contact pads of size 0.5 x 0.5 mm are placed symmetrically at the four sides of the chip. Half of the designs contain test junctions of area 10 μm^2 (TEST 10) and 25 μm^2 (TEST 25). There are 9 different types of chip designs on the mask. There are three variations of junction size available for each design type. They are marked by the symbols “-“, “+” and “ “ in the lower right corner. The junction area is 0.8, 1 and 1.2 $\mu m^{2,}$ respectivelyly.

5.6.7.4.5 Layer sequence

Table 5.9 summarizes layering structure of the chip. The microwave properties for SIS16 were calculated assuming thickness and materials from the table and the following junction parameters:

Trilayer RnA	25…30 $\Omega\times\mu m^2$
Junction quality factor	> 15
Junction area	Set of 0.8, 1 and 1.2 μm^2.

Table 5.9 - Layer structure

	Name	Material	Thickness	Maskplate ##	File name	Definition
1	Base electrode	Nb	100 nm	Mask0	Sis16m0	Liftoff
2	Junctions	Nb/AlOx/Nb	100/1/100 nm	Mask1, Mask2	Sis16m1	Etch
3	Dielectric	SiO_2	300 nm	Mask1, Mask2	Sis16m2	Liftoff
4	Counter electrode	Nb	>400 nm	Mask3	Sis16m3	Etch
5	Gold	Al/Gold	>100 nm	Mask4	Sis16m4	Lift off

5.6.7.4.6 Tolerances

The tolerance of all structures in the mask unless specified in the following must be better than **0.5 mm** for mask0 … mask3 and **1 mm** for mask4. Tolerances for “critical dimensions” and the smallest structure size are specified in Table 5.10.
The dimensions in mask 1,2,3 layers are corrected for technological parameter deviations. For the **counter electrode** it is assumed that all line widths are **decreased by 0.3 mm**, for the **junction definition layer** it is assumed that the final dimensions will be **decreased by 0.4 mm** as a result of all processing steps.

5.6.7.4.7 Alignment

The alignment markers (Figure 5.46) on this mask allow to align layers 1…4 with respect to layer 0. There are coarse and fine alignment elements. Nonius type structures technically allow to align layers within ± 0.05 μm. The required alignment tolerance is **± 0.25 mm**. This means that the two following layers can be misaligned by not more than **0.5 mm**. The marker for each layer is supplied with its own number.

Table 5.10 - Tolerances for critical dimensions for mask set SIS16

Layer name	GDSII file name	GDSII layer number	Smallest size (mm)	Tolerance (mm)*	Mask type
Base electrode (ground plane)	Sis16m0.gds	1	3.5 (slot)	± 0.3	“Negative”
		2	5 (slot)	± 0.5	
Junction definition 1	Sis16m1.gds	1	1.2 (line)	± 0.1	“Negative”
		2	5 (line)	± 0.5	
Junction definition 2	Sis16m2.gds	1	1.2 (line)	± 0.1	“Negative”
		2	5 (line)	± 0.5	
Counter electrode (wiring)	Sis16m3.gds	1	2.7 (line)	± 0.1	“Negative”
		2	5 (line)	± 0.5	
Gold pads	Sis16m4.gds	1	20 (line)	± 1	“Negative”

*Tolerances are specified as the absolute deviation of line (slot) width.

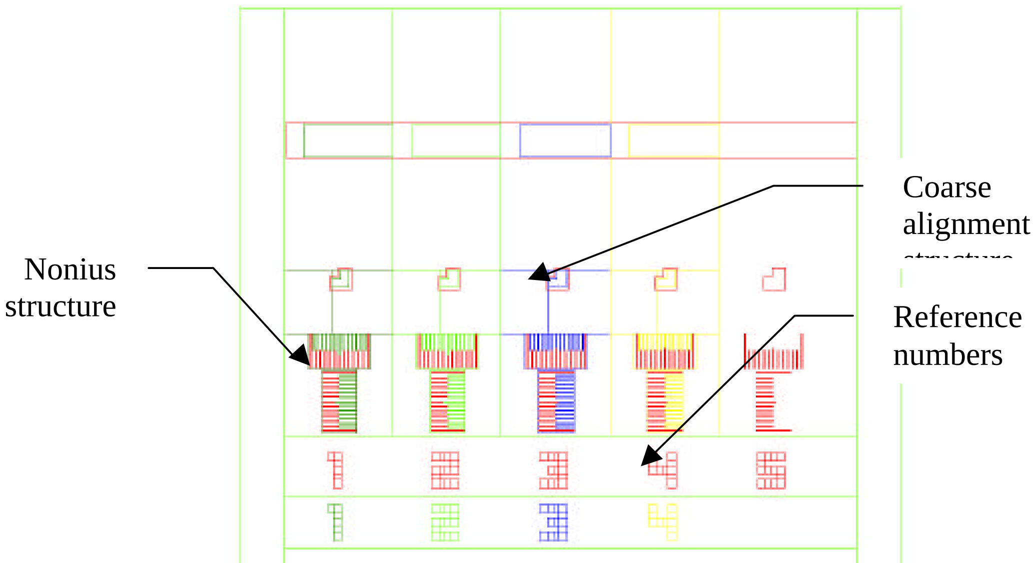

Figure 5.46 - SIS16 alignment markers structure. The base electrode is shown in red. Numbers in the figure correspond to layer numbers.

5.6.7.4.8 Other materials and technologies

The current design is tuned up for standard Nb/AlOx/Nb junction technology. The same mask set can be used without any modification with very high current density junctions (RnA=15 Oμm^2). These junctions could be made using a novel Nb/AlN/Nb process.

5.6.7.5 Single-ended 650 GHz mixer

Figure 5.47 shows a photograph of a so-called "D band" mixer, which is in use at the JCMT. The design tried to minimize the number of pieces and opted for simplicity. The mixer itself consists of a back piece, which holds the SIS junction and a corrugated feed horn (fabricated at RAL, UK), to which an Al lens holder is attached. Figure 5.48 shows the mixer noise temperatures across the *rf* band from 620 to 710 GHz for three different D-band mixers (called D5, D6, and D7). These fixed tuned SIS mixers provide a large *rf* bandwidth of about 150 GHz (Figure 5.49). The dip at around 560 GHz stems from water absorption in the atmosphere.

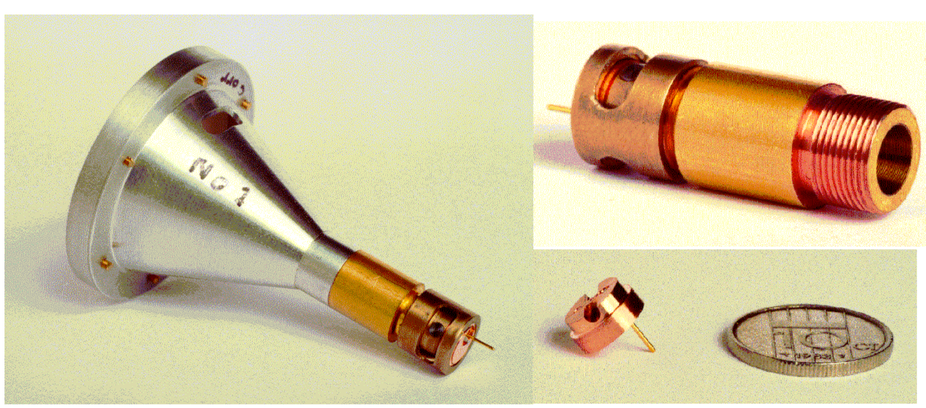

Figure 5.47 - Fixed tuned SIS mixer for the JCMT D-band (625 to 710 GHz) basically consisting of a corrugated horn (upper right) and a junction end piece (lower right). The larger aluminum piece (left) is a lens holder.

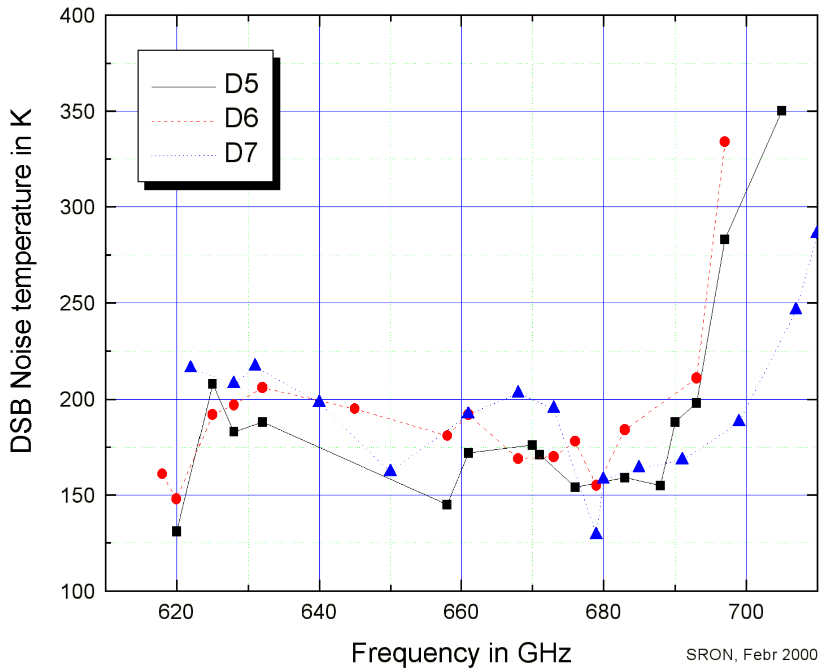

Figure 5.48 - DSB noise temperatures for three different D-band SIS mixers.

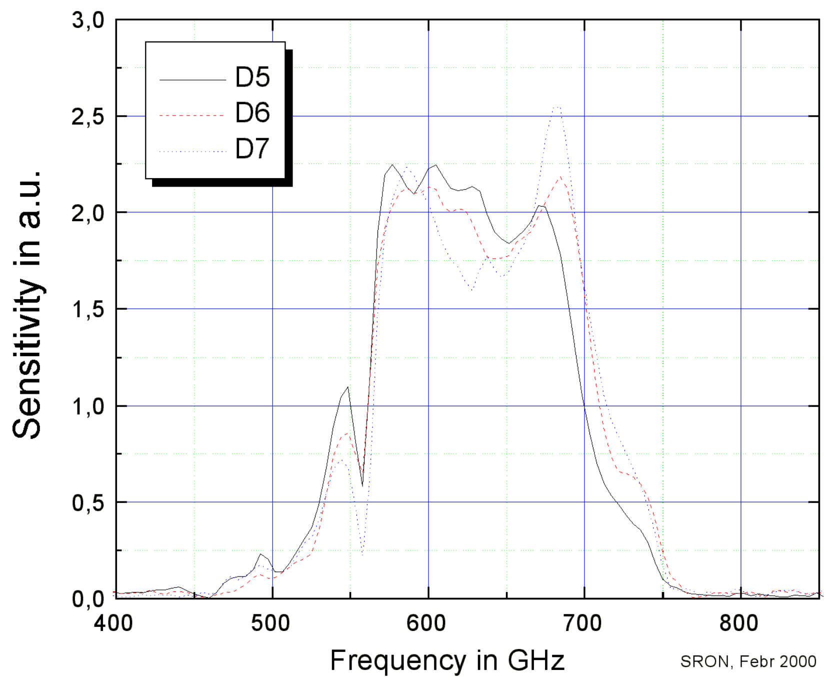

Figure 5.49 - Bandwidth of three fixed tuned SIS mixers. The mixers have been optimized for operation at 690 GHz.

5.7 The Water Vapor Radiometer.

A short version of the WVR proposal by Hills, Belitsky et al. could be inserted here. The original has 12 pages.