Development of a 0.6 THz SIS Receiver for ALMA

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ABSTRACT

The Atacama Large Millimeter Array (ALMA) requires low noise SIS receivers for frequencies from about 80 GHz to 950 GHz with very large IF bandwidth (4-12 GHz). Additional requirements for these receivers are high reliability, low cost and the possibility of series production. In this paper we report on mixer designs based on standard Nb/AlO_x/Nb SIS junction technology and an optics design for ALMA band 9 (602 – 720 GHz).

We present the design of a tunerless balanced waveguide SIS mixer and a quasi-optical double slot-antenna mixer as well as an optical design to couple the telescope beam to the mixer. The waveguide balanced mixer is based on a magic T with integrated RF and LO feed horns.

Losses in the Nb film increase at frequencies above the Nb gap frequency of 690 GHz and limit the mixer sensitivity at the high end of ALMA band 9. In this paper we present a layout concept of the optics and the mixers as well as an analysis of its RF properties which shows that efficient mixer operation is still possible across this band without changing the material of tuning elements.

INTRODUCTION

The Atacama Large Millimeter Array (ALMA) requires low noise SIS receivers for frequencies from about 80 GHz to 950 GHz with very large IF bandwidth (4-12 GHz). ALMA will be built in the Atacama Desert (Chili) at the altitude of more than 5 km. The atmospheric conditions for mm wave astronomical observations at this site are among the best in the world. The array will consist of at least 64 antennas, each with a diameter of 12 m.

Table 1, ALMA frequency coverage

Band	Low end frequency (GHz)	High end frequency (GHz)
1	31	45
2	67	90
3	84	116
4	125	163
5	163	211
6	211	275
7	275	370
8	385	500
9	602	720
10	787	950

The Alma frequency band is divided into ten subbands that are shown in table 1. These bands coincide with regions where the atmosphere is relatively transparent and astronomical observations are possible. The receivers for the different subbands will be mounted in a common cryostat supporting three temperature levels: 4.3 K, ~10 K and 80 K. Each subband receiver is contained in an independent "cartridge" that can be mounted in the receiver cryostat without disturbing other subbands. This cartridge contains a complete receiver system including SIS mixers, LO subsystem, IF amplifiers and all necessary optical components.

The remoteness of the site and the large number of receivers impose additional requirements to the receiver design such as: absence of moving parts, an as simple as possible layout, low cost, and the possibility of series production.

In this paper we report mixer designs based on standard $Nb/AlO_x/Nb$ SIS junction technology in waveguide or planar antenna geometries and a concept of an optics design for ALMA band 9 (602 – 720 GHz).

OPTICAL DESIGN

The ALMA telescope baseline design provides a beam with an f-ratio of f/8. Our goal is to design a frequency-independent optical system that matches the telescope beam with a mixer feed which consists of a corrugated horn in the case of the waveguide mixer or an antenna/lens combination in the case of the quasi-optical mixer. Additional requirements are low RF loss, low distortion loss, and low cross polarization loss. The latter is especially important for the polarization observations that are planned for ALMA.

We propose a configuration for the signal path consisting of two elliptical mirror. This creates enough flexibility to accommodate mixer feeds with f-ratios from f/3 to f/10. Two elliptical mirrors can be arranged in such a way that distortions introduced by them are partially compensated [1]. The proposed mirror arrangement is shown in fig 1.

The focal points (*fp1..fp4*) of the ellipses are indicated in the figure. The telescope secondary focus is located in *fp1* and the feed at *fp4*.

The coupling loss L_{dist} between the reflected beam and a symmetric Gaussian beam in each mirror is given by the following formula [1]:

$$L_{dist} = \frac{w_1^{\,2}\tan^2(\alpha 1)}{8 \cdot f_1^{\,2}}, \qquad (1)$$

where w_1 is the beam radius at the mirror, f_1 is focal length of the mirror and $\alpha 1$ is the beam bending angle as indicated in fig. 1. We assume that the second mirror compensates the distortion in the first mirror. Applying equation (1) to each of the mirrors and equating the result in the geometrical optics limit, one can obtain the following relation between the bending angles of the ellipses for full distortion compensation:

$$\alpha 2 = ArcTan\left(\frac{(1+\mathrm{M1})\cdot\tan(\alpha 1)}{\left(1+\frac{1}{\mathrm{M2}}\right)}\right), \qquad (2)$$

where M1 and M2 are the magnifications of the ellipses given by $M1 = \frac{R2}{R1}$ and $M2 = \frac{R4}{R3}$ (parameters are indicated in fig. 1). This equation can also be derived by means of minimizing geometrical aberrations. In the 600-720 GHz band, the beam radii become significantly different from the ones given by the geometrical optics calculation and equation (2) should be modified to incorporate Gaussian beam formalism. The bending angle relation then becomes frequency dependent. However, it is still possible to compensate distortions over a limited frequency range. Using the described approach, equation (2) can be easily extended for three or more mirrors.

The cross polarization loss is twice that given by equation (1) [1] and it can be compensated. Consequently, the approach described above holds for cross-polarization loss as well.

The final signal path layout for ALMA band 9 is shown in fig. 2.

SINGLE-ENDED WAVEGUIDE MIXERS

1. *Mixer design*

The single-ended waveguide mixers have been shown to have a quantum limited sensitivity [2], [3]. In the past, the SRON laboratory in Groningen has made sensitive SIS waveguide mixers for the 540-700 GHz frequency range. In February 2000 two of these were installed at the James Clerk Maxwell Telescope (JCMT) on Mauna Kea, Hawaii. The Double Side Band (DSB) receiver noise temperature of the present tunerless mixers is below 200 K over the whole band. The SSB system noise temperature, including all optics and diplexers of the W-band receiver at JCMT is below 600 K over the 630-700 GHz band.

Three mixers were made in total, two for the receiver and one spare. They are labeled D5, D6 and D7, where D7 is the spare mixer. We describe the mixer parameters in the following paragraphs:

The mixer consists of two sections: a front part including the corrugated horn and Teflon lens, and a back part with the substrate channel and IF connection.

The corrugated horn was designed by S. Withington of MRAO, Cambridge, England. It has a semi-apex angle of 7.5 degrees and a length of 19 mm, corresponding to a waist of 1.15 mm radius located halfway the horn length for the design frequency of 682 GHz. The waveguide has a cross-section of 100 x 400 μm. The lens is made of Teflon and has a focal length of 32 mm so that it gives good coupling between the horn and a 2.97 mm waist located 86 mm in front of the lens.

In the back part of the mixer the cross-section of the substrate channel is 70 x 100 μm and the backshort cavity is 160 μm deep. The substrate is 2.1 mm long, 50 μm thick and 70 μm wide and it contains a Nb-based SIS tunnel junction. It is glued in the channel and we use silver paint for the ground contact on one end as well as for the IF contact at the other end. For the IF contact we use a standard 50 Ohm glass bead.

The lens, horn and back part are contained in a mounting bracket, which is cooled at the top via a heat strap. The IF pin of the mixer fits into a standard SMA connector which is supported by a separate mounting bracket.

For the magnet we use a coil of about 6000 windings of 63.5 micron diameter Cu-cladded Nb wire. For the core of the magnet and for the field line conductors we use VacoFlux 50, which has a maximum permeability of 9000 and saturation polarization of 2.35 T.

2. *Sensitivity*

The Michelson FTS measurements for the D-band receiver are presented in fig. 4. It shows a relatively flat frequency direct response over the 560-700 GHz band for all three produced D-band mixers. The model calculation fit is shown in the same picture. The model includes Mattis-Bardin theory [2] for losses in the superconductor, standard lossy microstriplines and a waveguide probe approximation. All responses in fig. 4 are normalized. This model produces a remarkably good fit to the experimental data, for large variations of junction area or backshort cavity depths.

The measured noise temperature for the D-band mixers is presented in fig. 5. The measurements were done using standard Y-factor techniques. The center IF frequency was 4 GHz as required for the JCMT. The best noise temperature measured under these conditions is 170 K at 660 GHz (corrected for beamsplitter loss). The main source of noise in the system appeared to be the IF amplifier chain which at the time of the measurements was around 14 K. This can be demonstrated by a significant improvement in DSB noise temperature that we have obtained with a similar single-ended waveguide mixer at 1.5 GHz IF frequency. The uncorrected noise temperature for this mixer is shown in fig. 6. The best noise temperature, measured at 645 GHz, was 130 K. All noise temperatures are Callen & Welton corrected [5].

The receiver DSB noise temperatures of around 350 K across the band was registered at the JCMT using the fixed-tuned D-band mixers described above. The SSB noise temperature of 600 K was measured at the upper part of the band.

SINGLE-ENDED QUASI-OPTICAL MIXERS

The planar antenna – silicon elliptical lens combination was used successfully before to produce a usable receiver beam [6], [7], [5], [9]. A design similar to the one described in [9] is currently being implemented and tested. The design layout of such a mixer is presented in fig 7.

The RF signal is picked up from the double slotline antenna by means of stubs and then fed through microstripline transformers to a twin junction circuit. The DC and IF signals pass through the choke structure to the edge of the chip. The magnetic field required for Josephson current suppression is applied by means of passing a current through the wiring electrode just above the junction pair.

The FTS measurements of two quasi-optical mixers are presented in fig. 8 (on the same relative scale). One of these mixers was tuned at a somewhat higher frequency because of a smaller junction area. The considerable loss of sensitivity that is observed can be explained by increased loss in the Nb tuning structures above the gap frequency of Nb. The mixer with the optimal junction area produces a good response over the whole ALMA band 9, including the upper edge.

The quasi-optical mixers have certain advantages over waveguide mixers, mainly because of the smaller number of critical technological steps that are required for manufacturing, resulting in reduced production costs. For instance, a lens is cheaper than a good corrugated horn at these frequencies. Also, a few additional features like integrated Josephson current suppression can easily be implemented on-chip, obviating the need for an external superconducting magnet coil.

BALANCED MIXERS

The balanced mixers contain two individual mixer detectors which are pumped by local oscillator signals having a phase difference of 180°. This allows combining the IF signals in a 180° hybrid circuit so that the total signal is directed to one output port, while the LO sideband noise is directed to the other output port where it is dissipated in a load resistor. In this way one separates the local oscillator noise from the signal. This feature is especially important when using solid state local oscillators with a chain of multipliers, which generate a high level of sideband noise. The exact amount of sideband noise reduction depends on the accuracy of the 180° phase shift and on the amplitude balance between the two mixers [10]. However, it was shown that the amplitude and phase balance requirements are not stringent in this configuration. An additional advantage of balanced mixers is that all of the LO power is used without the additional complexity of having to build an LO diplexer.

The basic property of a balanced set of detectors is the phase-difference of 180° between reflected and transmitted waves. This can simply be achieved by using beamsplitters, as explained by Waite [11] using Stokes' analysis of phase change on reflection at a dielectric surface. Waite shows that this phase difference occurs automatically, independent of wavelength, polarization and angle of incidence, but that it is only exactly 180° for beamsplitters without absorption loss. An early demonstration of balanced mixers for heterodyne detection at a near infrared wavelength of 3.39 micron, or a frequency of 88.5 THz, was given by H. van de Stadt [12].

Instead of one of the conventional LO coupling schemes for balanced mixers (a simple beamsplitter or a more complicated set-up using a Martin-Puplett interferometer), we present here schemes with all-waveguide (Magic Tee) and quasi-optical balanced mixers.

1. *Magic-Tee balanced mixer*

The proposed magic Tee waveguide balanced mixer layout is shown in fig. 9. It is based on D-band mixer layout, described in previous sections. The Magic Tee mixer utilizes two detector backpieces of exactly the same design as in single-ended mixer. The phase difference in LO between the two mixers is achieved due to the symmetry of fields inside magic-T that automatically makes it broadband. In addition, the smallest size of elements in such a design is larger than in branch-line waveguide hybrids designed for the same bandwidth, thereby simplifying the manufacturing process.

CONCLUSIONS

The distortion compensated optical design for coupling the telescope beam into the various mixer feeds is described. The single-ended waveguide mixer operation has been successfully demonstrated at the James Clerk Maxwell Telescope. The best receiver noise temperature of 130 K (uncorrected for optical loss and beamsplitter) was measured at 650 GHz in a similar mixer.

The quasi-optical mixer design which works in 600-720 GHz band is described and preliminary evaluated. Preliminary results show that Nb technology is sufficient to cover the desired frequency range.

The magic Tee balanced mixer is proposed for this band and its layout, based on reusing proven design concepts from the single-ended mixer, is described.

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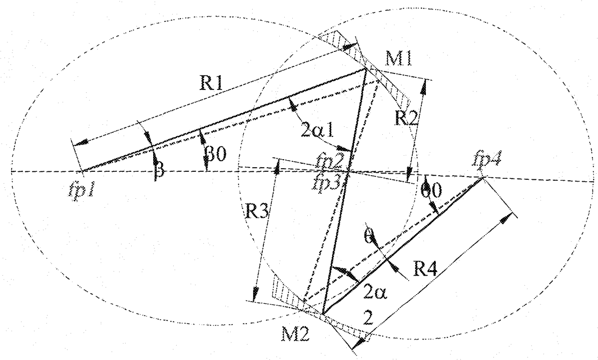

Fig. 1 Two elliptical mirrors distortion compensating arrangement

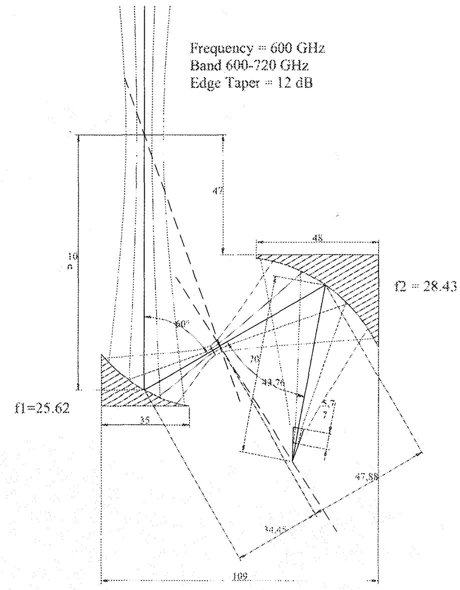

Figure 2: Proposed ALMA band 9 optical layout

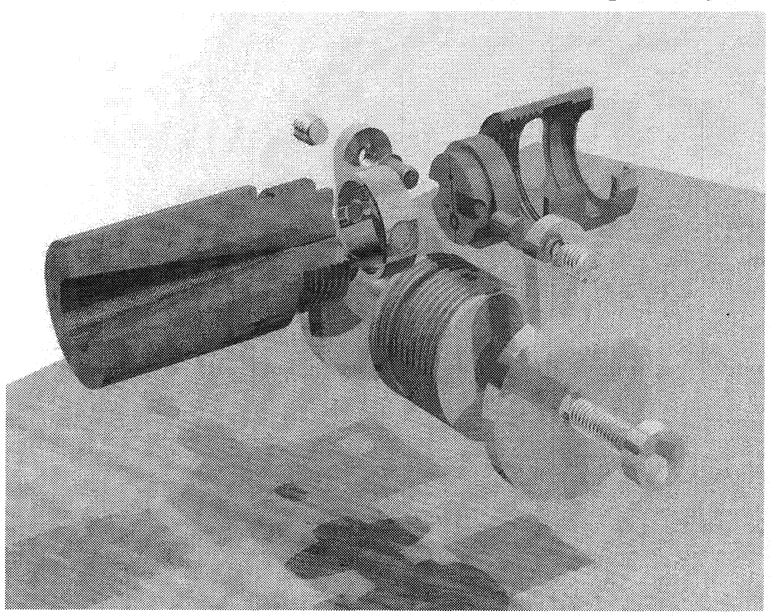

Figure 3: Exploded view of an SRON fixed-tuned waveguide mixer similar to the one installed at JCMT.

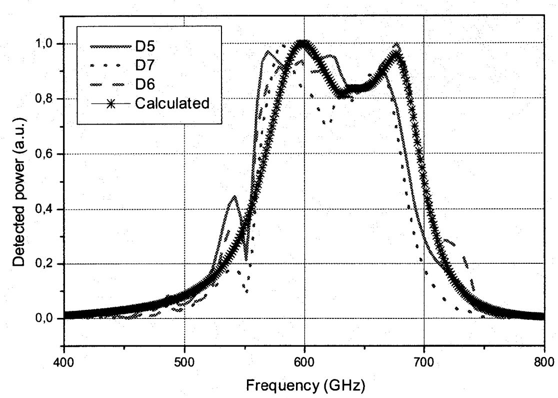

Figure 5: Receiver noise temperatures measured in the lab and at the JCMT.

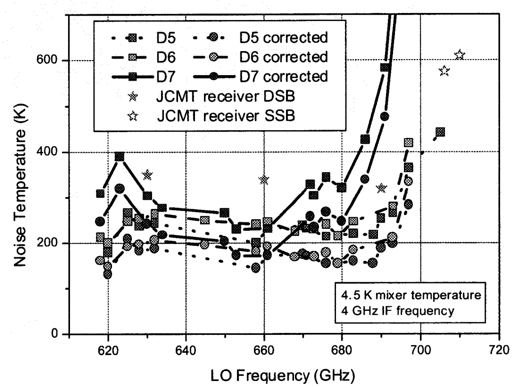

Figure 4: Measured FTS spectra for the three JCMT mixers (D5, D6, D7) and a prediction based on model calculations (crossed line).

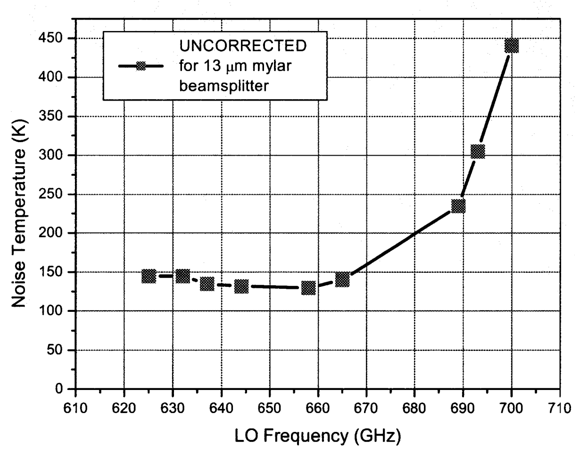

Figure 6: Uncorrected receiver noise temperature of a fixed-tuned waveguide mixer measured at 4.2 K physical temperature at an IF frequency of 1.5 GHz.

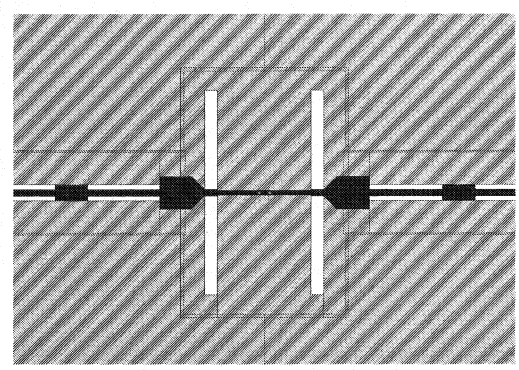

Figure 7: Chip layout of the quasi-optical SIS mixer for the 600-720 GHz ALMA band (not to scale). The SIS junctions are in the middle of the strip, and the double-slotline antenna and tuning structures are shown.

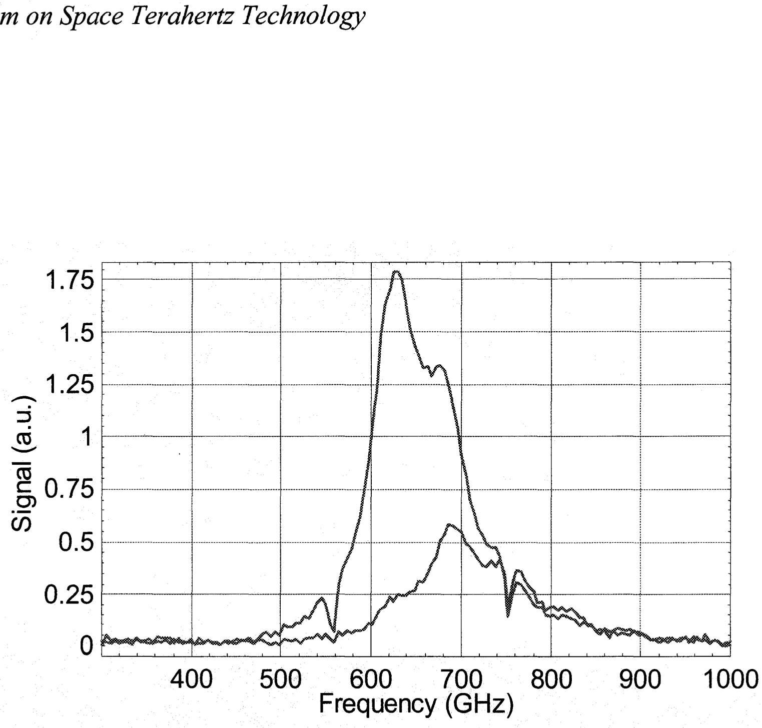

Figure 8: FTS response of two quasi-optical single-ended mixers. The mixer responses are shown in the same scale. The higher frequency peaked response is of the mixer with smaller junctions.

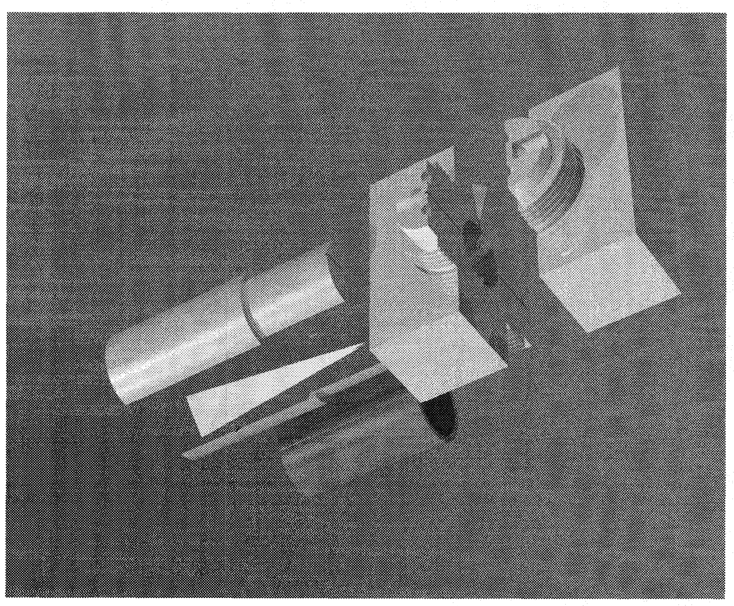

Figure 9: The Magic-T waveguide balanced mixer configuration. The two detector backpieces are not shown.