Journal of Physics: Conference Series **97** (2008) 012331 doi:10.1088/1742-6596/97/1/012331

# An SIS-based sideband-separating heterodyne mixer optimized for the 600 to 720 GHz band.

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**Abstract**. The Atacama Large Millimeter Array (ALMA) is the largest radio astronomical enterprise ever proposed. When completed, each of its 64 constituting radio-telescopes will be able to hold 10 heterodyne receivers covering the spectroscopic windows allowed by the atmospheric transmission at the construction site, the altiplanos of the northern Chilean Andes. In contrast to the sideband-separating (2SB) receivers being developed at low frequencies, double-side-band (DSB) receivers are being developed for the highest two spectroscopic windows (bands 9 and 10). Despite of the well known advantages of 2SB mixers over their DSB counterparts, they have not been implemented at the highest-frequency bands as the involved dimensions for some of the radio frequency components are prohibitory small. However, the current state-of-the-art micromachining technology has proved that the structures necessary for this development are attainable. Here we report the design, modeling, realization, and characterization of a 2SB mixer for band 9 of ALMA (600 to 720 GHz). At the heart of the mixer, two superconductor-insulator-superconductor (SIS) junctions are used as mixing elements. The constructed instrument presents an excellent performance as shown by two important figures of merit: noise temperature of the system and side band ratio, both of them within ALMA specifications.

## 1. Introduction

When detecting radio frequencies (RF) in the heterodyne mode, one has to distinguish between signals above or below the reference or local oscillator (LO) signal. DSB mixers downconvert signals above (USB) and below (LSB) the LO signal to the same intermediate frequency (IF). It is, therefore, necessary to suppress one of the RF bands before it is fed into the mixer. Extra instrumentation is thus required. A well known solution are 2SB mixers in which no previous filtering is needed as they provide two IF outputs corresponding to the two RF bands. This solution requires extra RF components that become prohibitory small at high frequencies. However, advances in micromachining technology permit attaining them for frequencies as high as 600 GHz. In fact, here we report the design, modelling, realization, and characterization of a 2SB mixer for frequencies from 600 to 720 GHz corresponding to band 9 of ALMA [1].

## 2. Design and Modelling

From a variety of possible 2SB schemes, we have selected the configuration shown in figure 1. The RF to be detected is brought to a hybrid which separates the signal into two branches of equal amplitude but with a phase separation of 90°. Each branch is coupled with the LO signal and mixed into two non-linear devices (SIS junctions in this case). The resulting IF signals are brought to a new 90° hybrid after which two new IF signals are obtained corresponding to USB and LSB, respectively.

We have opted for waveguide technology for the construction of the RF components and planar stripline for the IF filtering and matching parts. Each one the RF components and the planar IF system were modeled independently using commercial microwave-analysis software (Microwave Studio*). The dimensions of every RF component were selected for an optimal performance in the 600–720 GHz range. On the other hand, the IF signal is intended to cover 4–8 GHz.

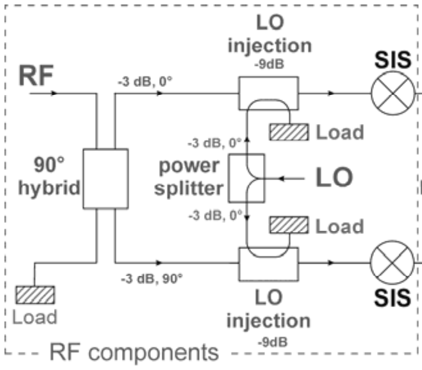


**Figure 1.** Schematics of the selected 2SB configuration. The incoming RF signal is divided in a 90° hybrid. The split signals are combined with an LO signal and then mixed into two SIS junctions. The resulting down converted signals are fed into a second hybrid after which the IF signals corresponding to the lower and upper sideband are obtained in two different channels.

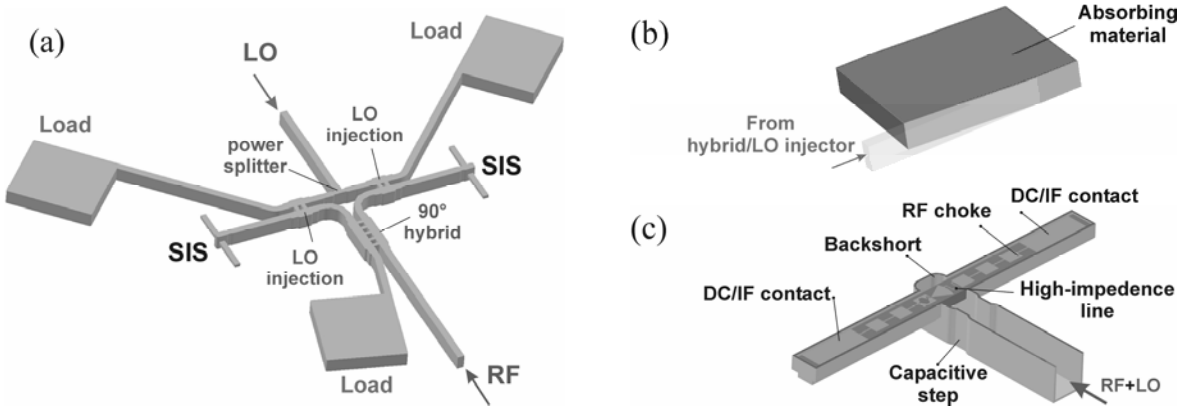


**Figure 2.** Design of the RF components indicated in figure 1: (a) The different components are designed in waveguide technique and, therefore, represent the channels to be machined out in the final split-block. Note that part of the split RF signal and part of the injected LO are dumped in termination loads. The transversal dimensions of the main waveguide are 145×310 μm$^2$. (b) Detailed view of the termination load. (c) Detailed view of the waveguide-to-SIS transition. The function of the different components is explained in the text. All figures are drawn to scale.

### 2.1. RF components

The design of the power divider, LO injectors, and 90° hybrid, figure 2(a), are based on a narrow bandwidth split block version developed for the ALMA project at lower frequencies [2]. However,

* Computation Simulation Technology, http://www.cst.com.

here, the waveguide width of the hybrid and the LO injectors has been increased by a 32.5% to maximize the thickness of the branch lines [3]. Every one of these components was simulated and optimized using commercial software. The results, summarized in figure 3(a), show a rather flat response of the devices in our frequency window.

We have selected a rather simple configuration for the termination loads. The design consists of a cavity at the end of the waveguide partially filled with an absorbing material as shown in figure 2(b). The geometry we are presenting here is relatively easy to achieve as the largest dimension is designed parallel to the splitting plane of the block. Extensive simulations of this configuration have been presented elsewhere [4]. The termination load show a good performance, as demonstrated by the reflection coefficient presented in figure 3(b), if Eccosorb MF112[†] is used as absorbing material [5].

We use a full height waveguide-to-microstrip transition to couple the incoming signal to the thin-film tuning structure of the SIS junction as shown in detail in figure 2(c). We have opted for a configuration that crosses the waveguide but in this case care must be taken in the way the DC bias return line meanders across the waveguide as this structure is prone to setup modal resonances [6]. An important modification is that we have added a capacitive step in front of the radial probe as it improves the overall performance [3]. For the RF choke we selected the popular "rectangular" structure. The calculated coupling efficiency and return loss, between the waveguide and the tip of the radial probe, are presented in Fig. 3(c).

Given the calculated S-matrices of the different RF components, we used a circuit simulator to calculate the sideband ratio (SBR), i.e. the ratio between the two IF output channels, of the complete RF core. The results are given in figure 4. If a perfect IF hybrid is assumed, a SBR above 20 dB is expected across the whole band. This sets the upper limit for the performance of the present mixer.

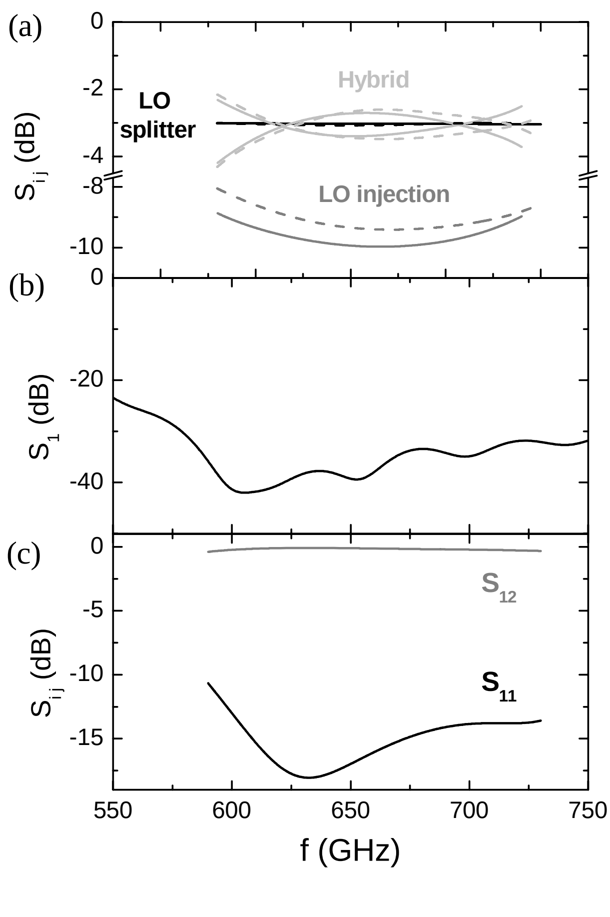


**Figure 3.** Results of the electro-magnetic simulation of the different RF components: (a) S-parameters between the input and output of the the 90° hybrid, LO splitter, and LO injector as designed, solid lines, and as constructed, dashed lines. (b) Reflection coefficient of the signal termination load. (c) Coupling efficiency and return loss of the waveguide-microstrip transition.

[†] Emerson & Cuming, http://www.eccosorb.com.

### 2.2. SIS junction and tuning structure

Based in our successful experience with the development of DSB receivers for band 9 of ALMA, we have opted for a single Nb/$AlO_x$/Nb junction devices as detection elements for our receiver. Although junctions using AlN as barrier have intrinsic better properties [7], we have selected the former as, at the moment, its fabrication process is much more reliable. The reasons for which the single junction approach is preferred are twofold. First, it permits an easier suppression of the Josephson currents across the junction and, second, it allows less effort in finding reasonably matched mixers.

Given the resistance-area product, $R_nA$, of $AlO_x$ junctions (~20 $\Omega.\mu m^2$), we have selected the area of the SIS junction to be 1 $\mu m^2$ [8]. The resulting SIS impedance has to be matched with the impedance at the radial probe tip which is calculated through the S-parameters given in figure 3(c). The matching is obtained by a multisection stripline made of Nb. For a given stripline geometry, it is possible to calculate the total transmission from the radial probe tip and the SIS junction using the microscopic theory of superconductivity in the dirty limit and standard transmission line theory [5]. The geometrical parameters where changed as to get a good coverage of band 9. The result of the calculation is shown in the thick solid line of figure 5.

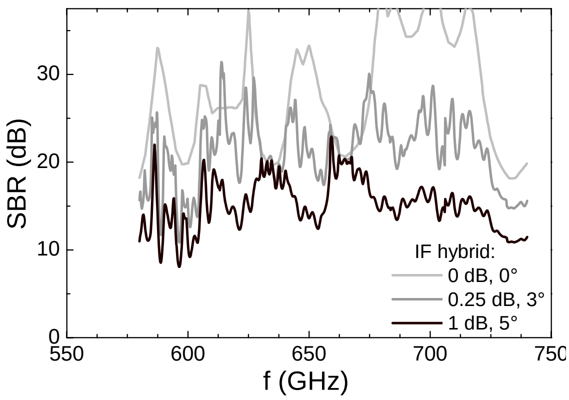


**Figure 4.** Calculated SBR assuming a perfect IF hybrid (light gray) and with a amplitude and phase imbalances of 0.25 dB and 3° (gray), and 1 dB and 5° (black).

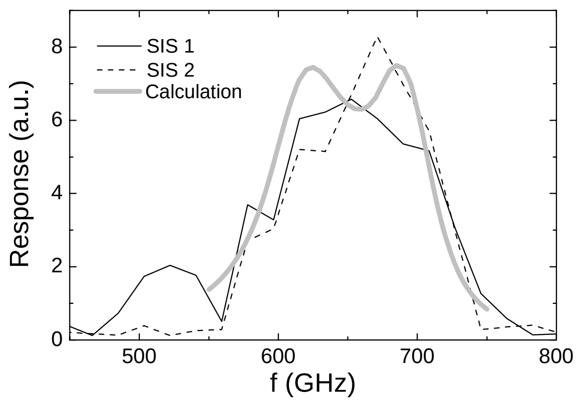


**Figure 5.** Calculated and measured response of the fabricated SIS junctions. The response was measured through the RF port.

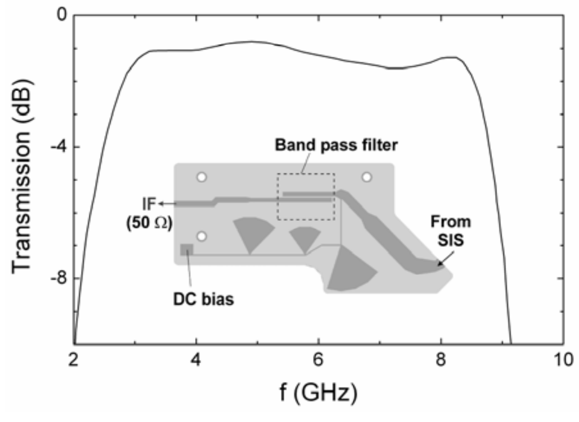


**Figure 6.** Calculated transmission between the input and output ports of the IF structure presented in the inset.

### 2.3. Planar IF filtering and matching

To facilitate reliability and modeling, we have opted for a planar IF filtering and matching design (inset of figure 6). This is a compact unit containing the IF match, DC-break, bias tee, and EMI filter.

It has to be noted that, for this filter to work, the ground plane directly underneath the filter has to be removed. The dimensions were optimized for a good performance in the 4 to 8 GHz frequency range. In the main frame of figure 6, we show the calculated performance of the IF circuit.

## 3. Construction

### 3.1. Waveguide block

We have constructed the mixer in a split-block (figure 7). We have used conventional machining for the large features and CNC micromachining for the small RF features [10]. Both parts of the block were made of copper which is gold platted afterwards with a thickness of ~2 μm. The fabricated unit is rather compact ($8 \times 2 \times 3$ cm$^3$). It contains all the RF components, the IF filtering board, the DC biasing circuit, and the magnetic probes needed to suppress the Josephson currents in the SIS junctions. A closer inspection of the fabricated block shows that all the waveguides and cavities are approximately 5 μm wider than designed. The reason appears to be the gold plating process as it etches away the copper that makes the block. However, the erosion is rather uniform through the entire block. We have repeated the simulation process with the measured dimensions [dashed lines in Fig. 3(a)]. It is clear that our design is pretty robust as long as the symmetry of the RF components is maintained.

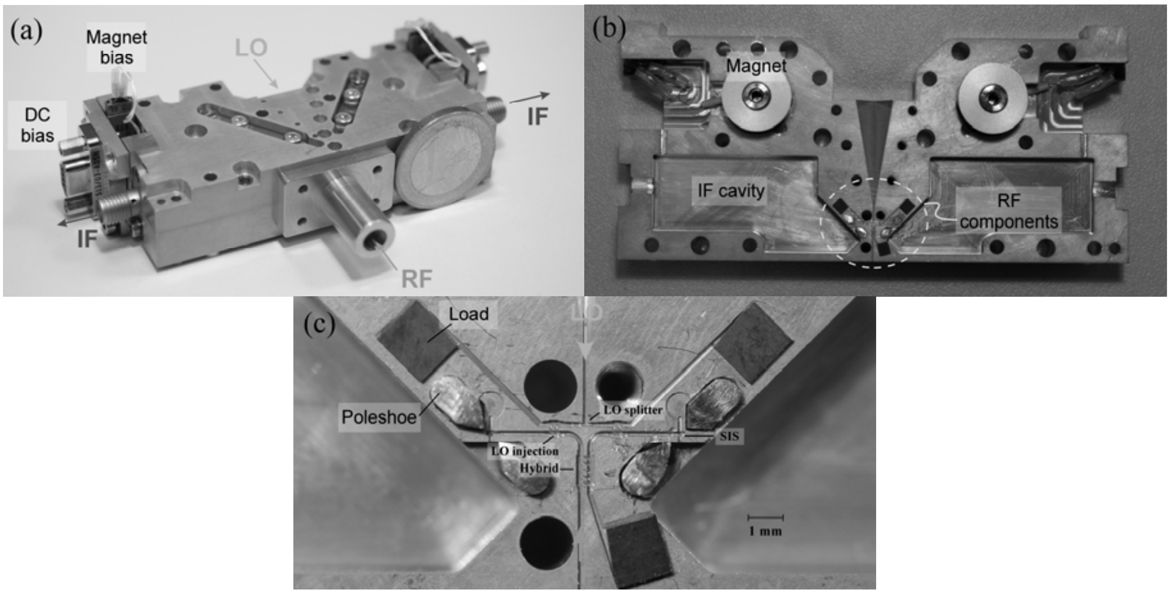


**Figure 7.** (a) Constructed 2SB block. (b) Upper half. (c) Close-up of the RF components.

### 3.2. SIS junctions

The SIS devices were fabricated on a quartz substrate. First, a Nb monitor layer is deposited, after which an optically defined ground plane pattern of Nb/Al/$AlO_x$/Nb is lifted off. Junctions are defined by e-beam lithography in a negative e-beam resist layer and etched out with a SF6/O2 reactive ion etch (RIE) using $AlO_x$ as a stopping layer. The junction resist pattern is subsequently used as a lift off mask for a dielectric layer of $SiO_2$. A Nb/Au top layer is deposited and Au is etched with a wet etch in a KI/I2 solution using an optically defined mask. Finally, using an e-beam defined top wire mask pattern, the layer of Nb is etched with a SF6/O2 RIE, finishing the fabrication process. This process renders a high yield and good reproducibility as demonstrated by the IV plots of 8 junctions (out of a sector containing 20 junctions) shown in figure 8.

## 4. Characterization

### 4.1. Band coverage

The direct response, as function of frequency, of both SIS junctions contained in our mixer has been measured using a home-made Fourier transform spectrometer. The results are presented in figure 6. Both junctions present good band coverage and are in good agreement with the predicted response.

### 4.2. Noise temperature and sideband ratio

Noise temperatures ($T_{RX}$) were measured using the conventional Y-factor method. As described in [11], the same setup was slightly modified to determine the sideband ratios. $T_{RX}$ and SBR for both output ports were determined at several LO pumping frequencies and recorded as function of IF frequency. The results are summarized in figure 9. Both quantities are rather close to ALMA specifications as indicated by the horizontal dashed lines. For $T_{RX}$, 80% of the band should not exceed 335 K while all points should be below 500 K [1]. The image rejection ratio, on the other hand, should always be above 10 dB. Although the noise temperature complies with ALMA specifications, it is obvious from figure 9 that the IF response presents a rather steep increase at high IF frequencies. The most probable reason is a mismatch between the SIS impedance and the IF unit. Further work has to be done in this aspect to improve the noise temperatures.

The obtained image rejection ratios are in close agreement with the modeling prediction given in figure 5 if an amplitude and phase mismatches of 1 dB and 5° in the IF hybrid are considered. These, indeed, are the experimental values obtained at 77 K [12]. It has to be noted that the hybrid used is a commercial one[‡] that has been optimized for operation at ambient temperature. It is reasonably to argue that mismatches of 0.25dB and 3° can be obtained by optimization of the design at low temperatures. In that case, an improvement of ~7 dB is expected (see figure 4).

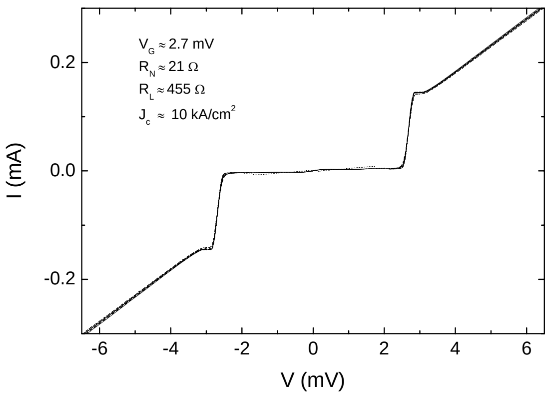


**Figure 8.** IV curves of 8 different junctions. The average values of gap voltage ($V_G$), normal resistance ($R_N$), leakage resistance ($R_L$), and critical current density ($J_C$) are shown.

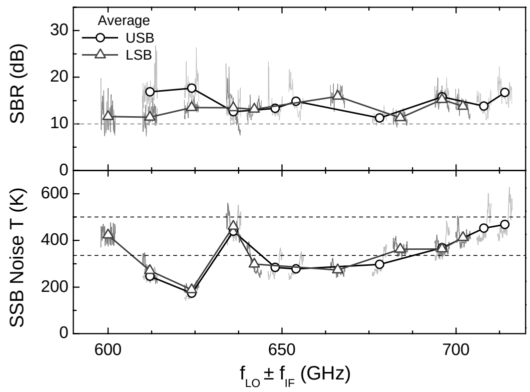


**Figure 9.** Single sideband noise temperatures (bottom panel) and image rejection ratios (upper panel) at different LO frequencies. Both parameters are close to ALMA specifications (horizontal dashed lines) described in the text.

## 5. Conclusions

In this article we have presented the design, modeling, and realization of a side-band-separating mixer that covers the frequency range of ALMA band 9. A full test of the mixer was also presented. It was found that lees than 10% of the points are below the required sideband ratio (10 dB) and above the specified noise temperature (500 K). However, further improvement can be achieved if the IF system is optimized and AlN-barrier SIS junctions are used, with which a full coverage of ALMA specifications are expected.

[‡] Advanced Technical Materials Inc., http://www.atmmicrowave.com/.

**References**

[1] ALMA web site, http://www.alma.nrao.edu.
[2] S.M.X Claude et al., Alma Memo 316, 2000.
[3] J. Kooi et al., SPIE, Millimiter and submillimiter detectors for Astronomy II, vol. 332, pp. 5498, 2004.
[4] F. P. Mena and A. Baryshev, Alma Memo 513, 2005.
[5] G. A. Ediss et al., Alma Memo 273, 1999.
[6] C. Risacher et al., IEEE Micro. and Wire. Comp. Lett., vol. 13, pp. 262, 2003.
[7] J. Kawamura et al., Appl. J. Phys. 76, pp. 2119, 1996.
[8] A. R. Kerr and S.-K. Pan, Int. J. Ir. & Mm. Waves, vol. 11, pp. 1169, 1990.
[9] C. F. J. Lodewijk et al., Conf. Proc. 16th ISSTT, pp. 42, 2005. Available online at: http://www.mc2.chalmers.se/mc2/conferences/ISSTT/ISSTT2005-proceedings.pdf.
[10] Radiometer Physics GmbH, http://www.radiometer-physics.de/.
[11] A. R. Kerr, S.-K. Pan, and J. E. Effland , ALMA Memo 357, 2001.
[12] S. Mahieu, Institut de RadioAstronomie Millimétrique, France, priv. comm., Jan. 2006.