Sideband-Separating SIS Mixer For ALMA Band 7, 275-370 GHz

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Abstract

Following the design for a sideband-separating mixer using a quadrature waveguide hybrid and an in-phase waveguide power divider and SIS mixer chips [1] experimental results of a dual side-band separating SIS mixer (2SB) for Band 7, i.e. 275-370 GHz are presented. This mixer uses DSB mixer units that can be tested separately prior to the 2SB operation. Image rejection over the full Band 7 is better than –10 dB. The results are encouraging at a prototype level and some more qualifications tests remain to be done before the full production of the 128 + spare units. The design is suitable for scaling at any other frequencies below Band 7.

1. Introduction

One of the ALMA frontend requirements is to produce fixed-tuned single-sideband receivers with an image rejection better than -10 dB. In the case of a 2SB mixer, the IF bandwidth must cover 4 GHz per sideband. The SSB noise temperature specification is 133K for the 275-370 GHz band and 198 K over a maximum of 20% of the band. One of the method to reject the image is to use quadrature hybid couplers in such a way that the Upper Side Band (USB) and the Lower Side Band (LSB) are simultaneously separated, as described in [1]. Design and experimental results are presented here for Band 7.

2. Concept

As described on Fig. 1 a sideband separating mixer consists of one quadrature hybrid coupler that will split the RF signal detected by the telescope in two and introduces a 90 deg phase difference between its outputs. The Local Oscillator (LO) is split in two with an in-phase power divider. At this point the LO and RF inputs are interchangeable. The LO and RF are combined through a -16dB coupler before being coupled to the SIS mixer. The IF signals of both mixers are recombined through a quadrature hybrid where the 90 deg phase difference will separate the USB and LSB.

Having in mind the goal of producing front ends for 64 antennas, the design of 128 2SB mixers must be simple to machine, assemble and test. Therefore an E-plane split block technique is used to produce, in the same part, the quadrature hybrid, the in-phase power divider and the two -16dB couplers. The mixers were chosen to be separate from the coupler in order to test them prior to the 2SB integration. And finally, the IF signals are recombined with a commercial quadrature hybrid before amplification.

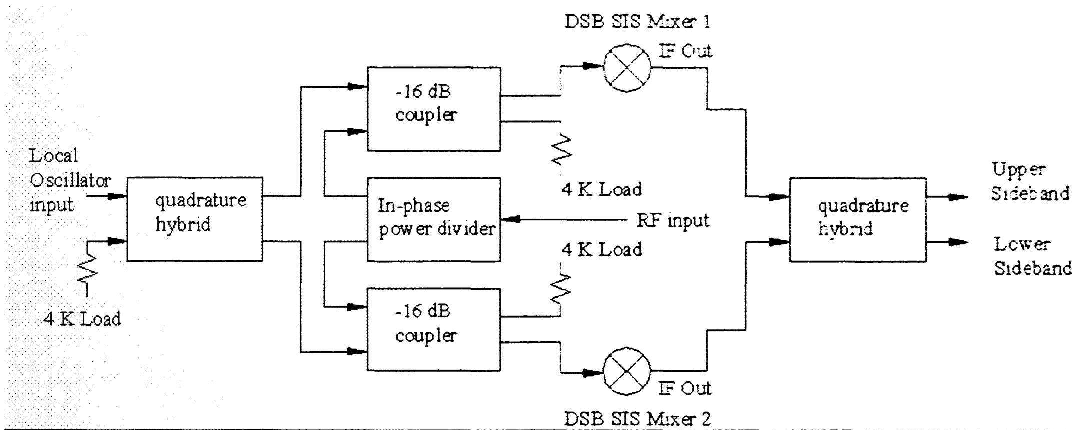


Fig. 1. Sideband-separating mixer.

As discussed by Kerr and Pan [2], the phase and amplitude imbalance is not very critical if image rejections better than -10 dB are to be obtained. For example, a 3dB amplitude imbalance and 30deg phase imbalance would lead to –10dB image rejection. However, the system must be kept symmetrical, in particular for the waveguides and the IF connections before the quadrature hybrid. Similar mixers imput mismatch and gain are important too.

3. Design of the components

a. Waveguide quadrature hybrid

Hybrid couplers have been designed and manufactured for ALMA band 7 (275-370 GHz) and a scale model at 195-260 GHz has been fully characterized with the IRAM Vector Network Analyzer (VNA) [3] and [4].

A hybrid coupler is a 3dB power splitter with 90 deg phase shift between the two outputs. The two waveguides are coupled through the broad walls and are separated by shunt guides $\lambda_g/4$ long. There is a minimum of two shunt waveguides, separated by $\lambda_g/4$, producing a narrow band device, and the bandwidth can be increased with the number of shunts (see Fig 2). However, for keeping the same 3dB coupling the width of the slots has to be decreased if the number of slots is increased. Dimensions of a quadrature hybrid at mm wavelength are quite critical particularly for a series production of 128. Simulations have been carried out with CST Microwave Studio (CST MWS) [5] in order to optimize the slot width and number, and the separation between the waveguides. It was found that a good trade off to produce 3dB coupling over the ALMA band 7 while having slots that can be realistically made in series is to have 5 shunts 0.133 mm wide, 0.350mm apart. Each half of the split mixer blocks contains square waveguides 0.38x0.38 mm that are separated by a 0.20 mm wall.
The scale model has 5 shunts 0.189 mm wide, 0.497 mm apart. The 0.545 mm square waveguide in each block are separated by a 0.279 mm wall. Table 1 gives a summary of the coupler's dimensions.

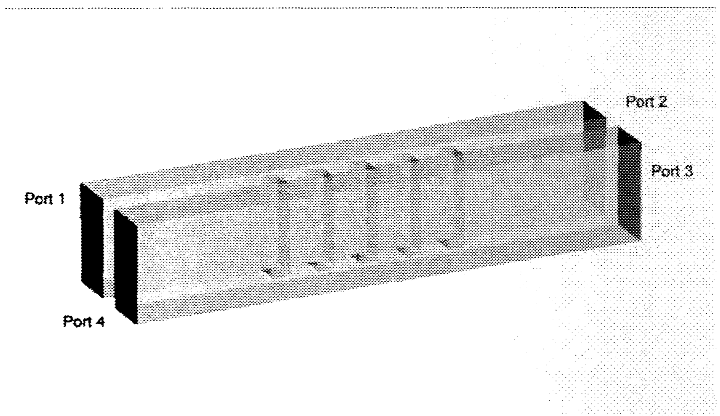


Fig 2 View of the hybrid coupler

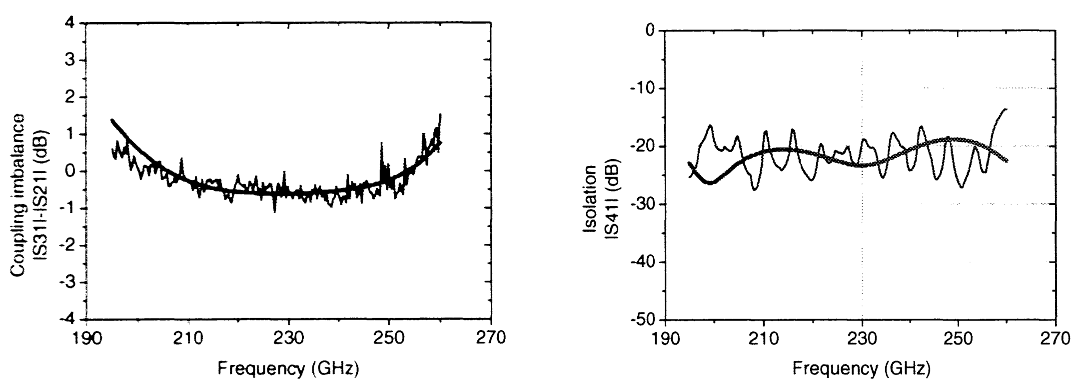
Frequency band	Waveguide size (mm)	Slot width (mm)	Slot pitch (mm)	Waveguide pitch (mm)
195-260GHz	1.090x0.545	0.189	0.497	0.824
275-370GHz	0.760x0.380	0.133	0.350	0.580

Table 1 Dimensions of the 3dB coupler

The blocks were machined with CN milling machine at IRAM, except for the 5 slots. Since the 5 slots for the 320 GHz coupler cannot be easily machined the technique of spark erosion was used. In order to reduce sparking in the bottom of the main waveguides, there is 0.02mm step between the bottom of the slots and the bottom of the main waveguides. Fig 2 shows a 3D drawing of the coupler.

Amplitude measurement

The amplitude measurements made with the IRAM VNA at 195-260GHz fit nicely the simulation done with CST MWS (Fig. 3). These measurements were done by injecting a signal through port 1, and the detection was done at port 2 and 3 for amplitude imbalance. The isolation was measured between port 1 and 4. Input reflection coefficient S11 is better than –20 dB across the band for all 4 ports.



a) b)

Fig 3 : CST MWS simulation (red smooth line) and measurement of a) amplitude imbalance and b) isolation.

Phase Measurement

The phase measurements were made with the IRAM VNA at 195-260GHz. Using the transmission method, as for the amplitude measurement, requires moving the mm detector module of the VNA from port 2 to port 3. The mm detector module is linked to the VNA with a flexible coaxial cable that carries the 13^{th} harmonic of the mm signal. Any movement of these cables will generate a phase shift. Therefore, a different method must be used to measure the phase difference between port 2 and 3. Instead, a reflection method can be used.
For that experiment, a -10 dB coupler was placed at port 1 so that emission and detection could be done at the same port. First, a load was placed at port 3 and a short circuit at port 2 so that the signal being detected at port 1 would have traveled the path port1-port2 twice. Second, the load and the short circuit were exchanged so that we detected twice the path port1-port3. The difference of these two measurements is equal to $2\text{x}\Delta\varphi$ (modulo 2π). The phase imbalance is then $\Delta\varphi$ (modulo π). Taking a linear fit in the data set we measure $\Delta\varphi$=82 deg, mid-band (see Fig 4). In that case, only the loads are moved thereby no phase offset were generated by the measurements. However, as shown in Fig 4, the VSWR of the ports to which the loads are applied produce some modulation in the phase imbalance measurement.

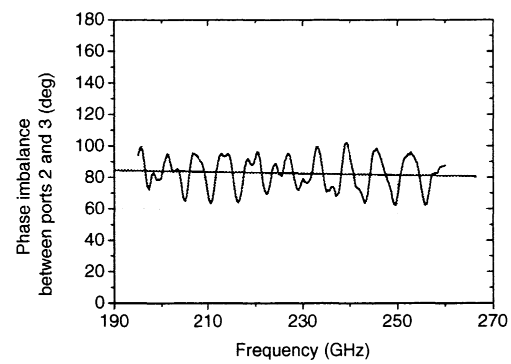


Fig 4: Phase imbalance measurement in transmission and linear fit.

b. -16 dB coupler

The coupler consists of two waveguides that are linked through the broad walls and are separated by shunt guides $\lambda_g/4$ long (See Fig. 5). There is a minimum of two shunt waveguides, separated by $\lambda_g/4$, producing a narrow band device, and the bandwidth can be increased with the number of shunts. For a given coupling, the slots widths have to be reduced if their number increases. A -16dB coupler at 320GHz will have two slots 0.060mm wide, representing the limit with present technology for reproducible high quality slots (see Table 2).

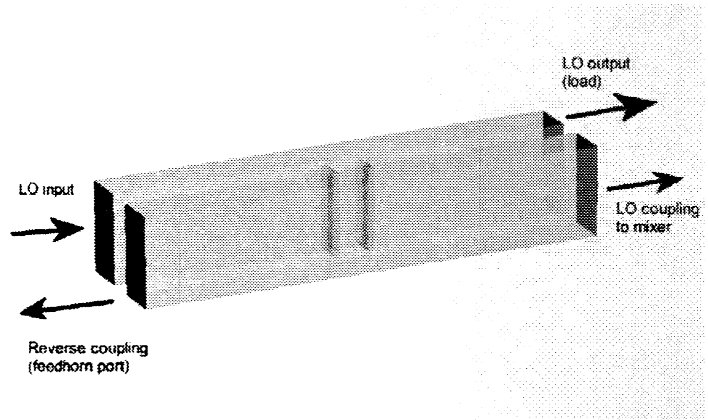
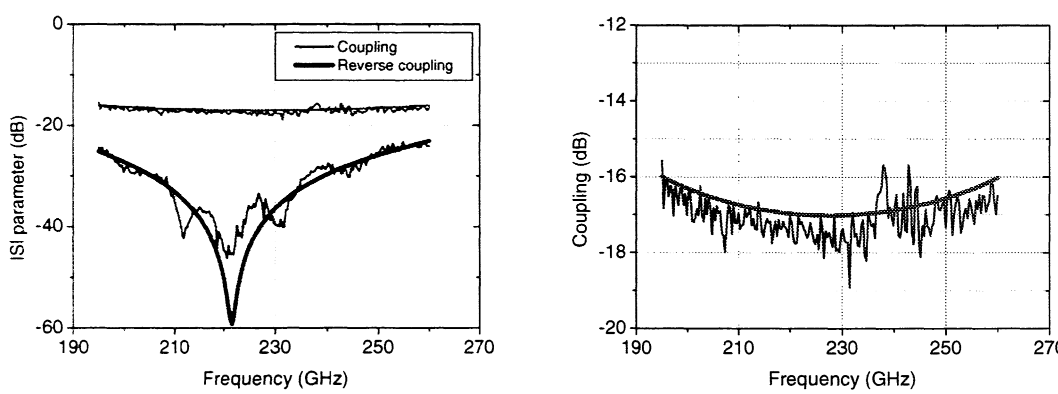


Fig. 5: View of -16 dB branch-guide LO coupler.

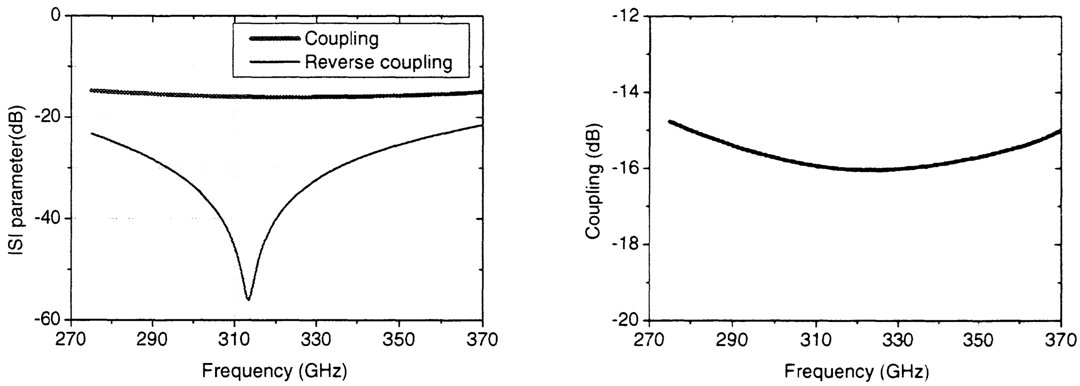
Frequency band	Waveguide size (mm)	Slot width (mm)	Slot pitch (mm)	Waveguide pitch (mm)
195-260GHz	1.090x0.545	0.080	0.440	0.875
275-370GHz	0.760x0.380	0.060	0.315	0.615

Table 2: Dimensions of the –16dB coupler

Simulations have been carried out with CST MWS in order to optimize the slot width and the separation between the waveguides. The resulting design covering Band 7 (275 GHz to 370 GHz) was tested with a scale model at 195GHz to 260 GHz, on the IRAM VNA. The coupling varies by 1dB across the band and the isolation is better than -10dB (see fig 6).



a) b)



c) d)

Fig. 6: a) and b) Simulation and measurements of the –16dB branch-guide coupler covering the band 195-260 GHz; measurements are the noisy lines c) and d) show CST MWS simulation for the 275-370 GHz coupler.

The blocks (see Fig 7) were machined with a CN milling machine at IRAM, except for the 2 slots that were spark eroded. In order to reduce sparking in the bottom of the main waveguides, there is 0.02mm step between the bottom of the slots and the bottom of the main waveguides. The load, absorbing the unwanted LO signal, consists of a wedge glued in the waveguide made of Alkar 66 (carbon and iron loaded epoxy absorbing material).

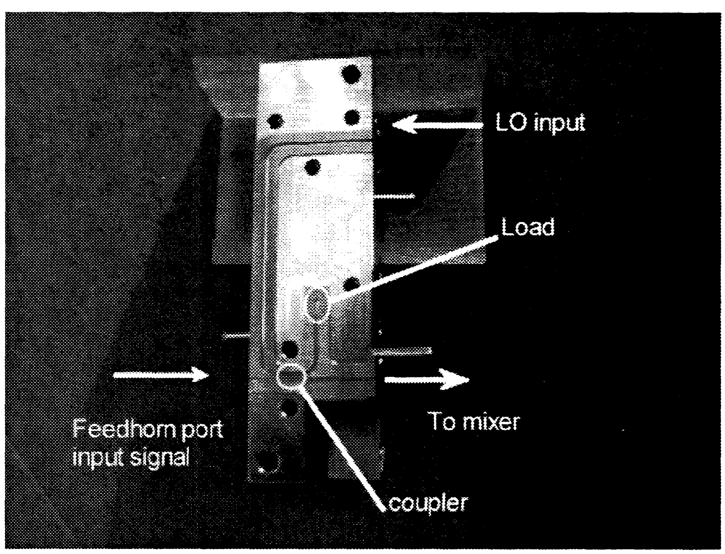
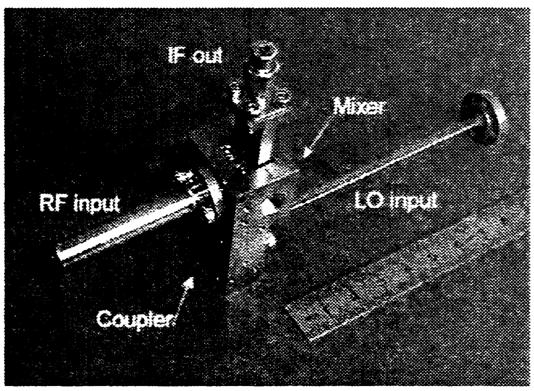
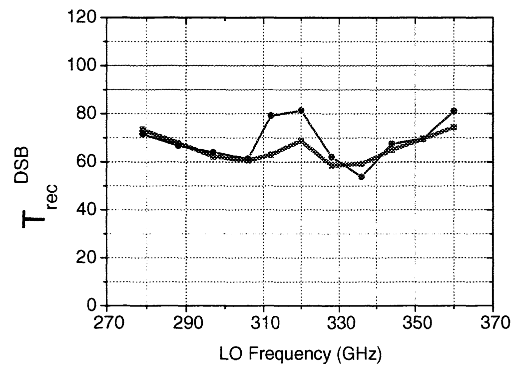


Fig. 7: One half of the 320 GHz coupler

c. DSB Mixer unit

The DSB mixers used in this experiment were designed by A.Navarrini [6]. In order to couple the LO signal to the mixer, the –16dB coupler was designed to be integrated with the back of the DSB mixer for reducing the input waveguide length (See Fig. 8 a). Two mixers coupler assemblies were measured as shown in Fig 8 b. It must be noted here that the two mixers did not have the best noise temperature in the batch but more importantly for this experiment had similar characteristics (I-V and noise temperature).





a) b)

Fig 8: a) Mixer coupler assembly for DSB Mixer test and b)DSB mixer units noise temperature with 4-8 GHz IF bandpass filter

The mixer design used for this experiment was originally targeted for 2GHz IF bandwidth. Here, in order to meet the ALMA requirements the mixer IF was measured over a larger bandwidth and filtered over the 4-8GHz band. As shown on Fig 12 a) the actual bandwidth of the mixer is 4-6 GHz and the output IF cuts off rapidly beyond 6 GHz.

d. In-phase power splitter

The in-phase power divider consists of a Y junction with 5 mm radii and has a CST MWS simulated S11 better than –20 dB across the band..

4. Sideband separating mixer

All previously described elements can be put together to form a compact sideband separating mixer. One half of the coupler is shown in Fig 9 with the location of the LO in-phase power splitter, the signal quadrature hybrid and the two –16dB LO couplers all machined on a single piece of brass. For each coupler, the un-used waveguide branch was terminated by a load . Fig 10 shows the complete mixer assembly. The LO signal is brought in with an overmoded WR-10 waveguide followed by a waveguide transformer to WR-3. Note that such a transformer can be implemented in the coupler. This non essential added complication in the design was not considered for the present demonstration prototype. The two DSB mixers with the IF impedance transformers fit on opposite sides of the coupler connected to the output waveguide of each –16dB LO couplers. The size of the coupler is dominated by the alignment pins and standard UG 387flanges. Each mixer IF output are directly recombined by a quadrature hybrid coupler. The two output ports of the quadrature hybrid correspond to the separated USB and LSB signals and after going through a bias tee, an isolator, a 34 dB gain 4-8 GHz HEMT amplifier with a noise temperature of ~4 K [7], for each band, the signals are taken out of the cryostat for filtering and further amplification. A good symmetry must be maintained between the two signal paths from the waveguide and IF hybrid couplers.

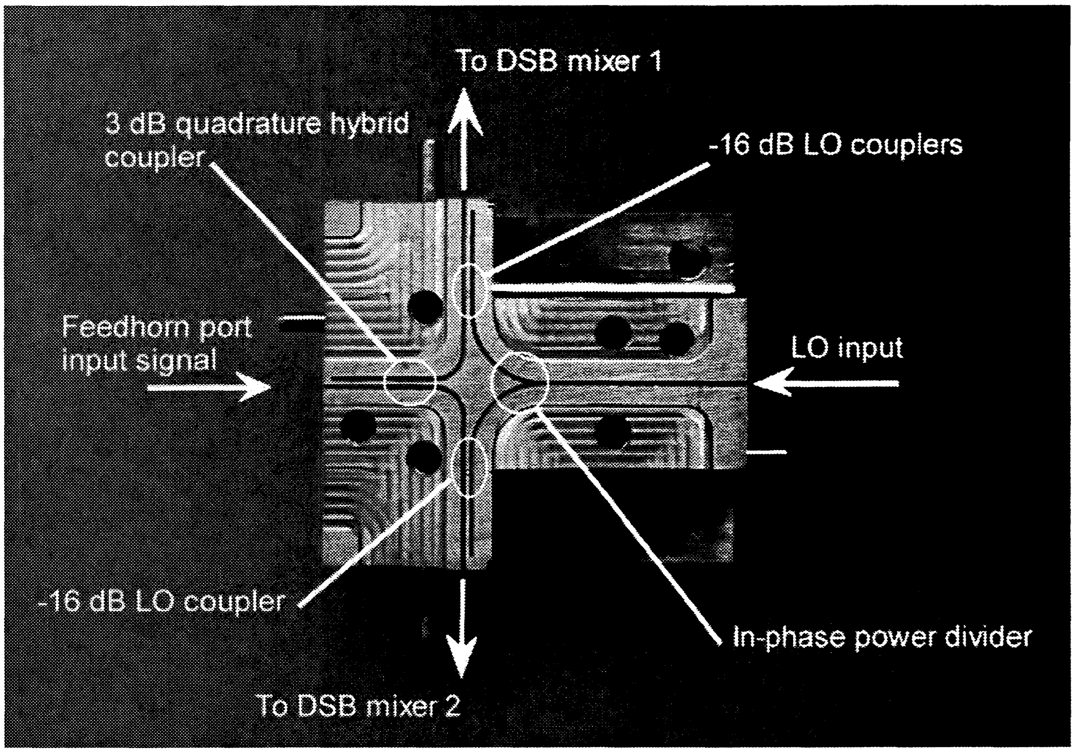
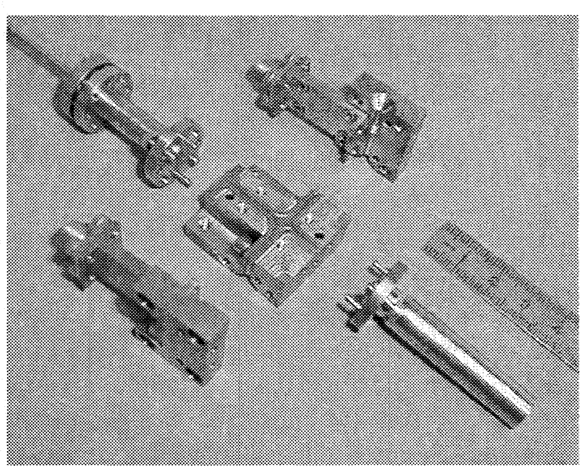
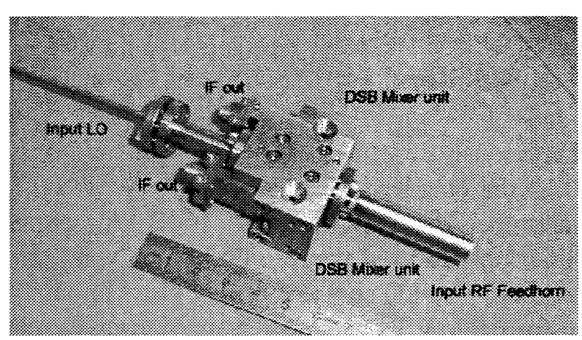


Fig 9: One half of the 2SB coupler.



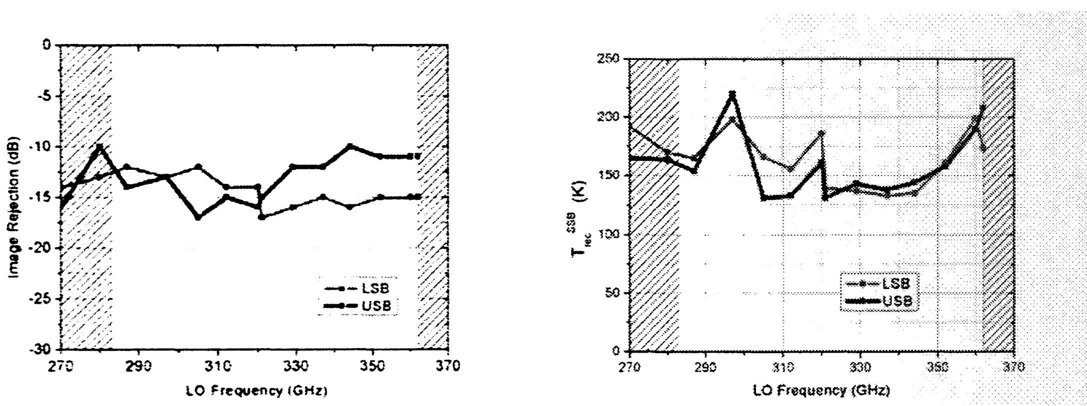


a) b)

Fig 10: 2SB mixer assembly a) open 2SB Mixer, b) assembled 2SB Mixer

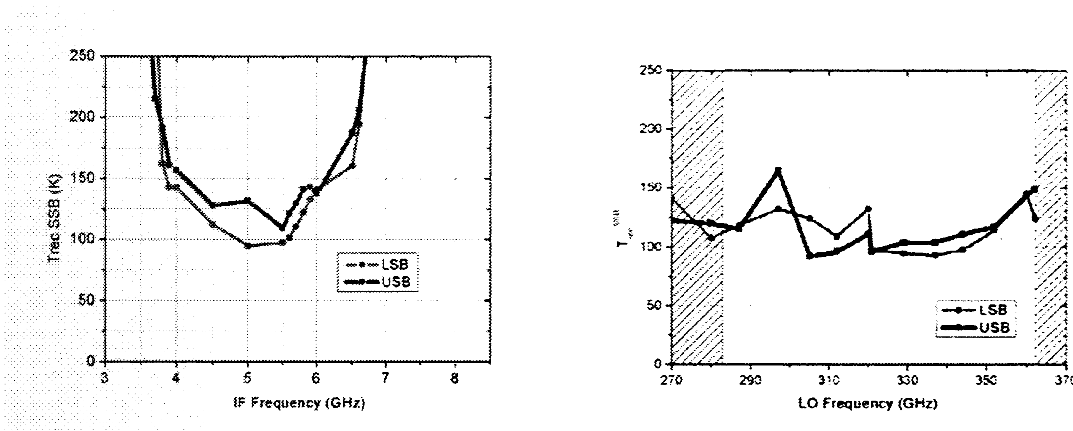
Two independent superconducting coils were used to suppress the Josephson currents. However, a good suppression was obtained with identical currents in both coils. A production mixer could have one coil in common, as described in [1. Tuning the mixers with bias and LO power proved to be quite simple, and not much different to a single ended DSB experiment. Each mixer bias could be tuned independently, which proved to be useful for a few frequencies where the mixer responses were not identical. In addition, for the same bias value the pump current of each mixer was very similar, showing the symmetry of the LO splitter and the similarities in the mixers reflection coefficients. The image rejection was measured with the method described in [8] with a narrow band (35 MHz) filter at the IF output and a harmonic mixer to inject an RF signal. As shown in Fig 11, the image rejection is between –10 dB and –15 dB across the band. And the SSB receiver noise temperature is close to twice the DSB noise temperature of each individual single ended mixers, as expected for such a system. This noise temperature were obtained with a 4-8 GHz IF. In order to cover the IF bandwidth required by ALMA, 4-8GHz IF must be used. However, as shown of fig 12 a) the mixers have a narrower bandwith. In order to estimate how the receiver noise would improve in a narrower band configuration, Fig 12 b) shows noise temperature measurement at 5 GHz IF with the 35 MHz bandpass filter used to measure the sideband ratio. The narrow band IF noise temperature is much improved compared to the 4 GHz wide band measurement. This effect is inherent of the DSB mixer units.

This experiment was done with two mixers having very similar DSB noise temperatures. Future experiments should show how important is the pairing of DSB mixers. That is particularly important for the production of a high number for ALMA. The yield must be determined for the matching of mixers since this would have a significant effect on the number of DSB mixer units to produce.



a) b)

Fig 11 a) Image rejection for the LSB and USB ports of the mixer b) SSB receiver noise temperature with a 4-8 GHz IF. The haches represent frequencies that are out of Band 7.



a) b)

Fig 12: a) Trec SSB at LO=336GHz over the IF band with a 4-8 GHz band pass filter. b)SSB receiver noise temperature with a 5 GHz IF, 35 MHz passband. The haches represent frequencies that are out of Band 7.

5. Conclusion

A sideband separation mixer was designed and tested for ALMA Band 7 (275-370GHz). Performances of this demonstration prototype proved that the concept could be used on a telescope. Image rejection better than -10dB is meeting the ALMA specifications. However, the noise temperature and the IF bandwidth of the mixer have to be improved in order to meet the ALMA specifications. Also, the yield for the pairing of the DSB mixers must be measured.

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References

[1] ALMA Memo #316
[2] A.R.Kerr and S-K.Pan, "Design of Planar Image Separating and Balanced SIS Mixers", ALMA Memo #151, March 1, 1996.
[3] F.Mattiocco and M. Carter, "80-360 GHz very wide band millimetrer wave network analyzer", International Journal of Infrared and Millimeter Waves, Vol.16, No 12, 1995.
[4] F.Mattiocco, M. Carter and B.Lazareff, "220-230GHz harmonic mixer for a full band sweep vector network analyzer", International Journal of Infrared and Millimeter Waves, Vol.21, No 11, 2000.
[4] CST Microwave Studio. Büdinger Str. 2 a, D-64289 Darmstadt, Germany.
[6] A. Navarrini, B. Lazareff, D. Billon-Pierron, and I. Peron, "Design and characterization of 225-370 GHz DSB and 250-360 GHz SSB full height waveguide SIS mixers", Thirteenth International Symposium on Space Terahertz Technology, March 26-28, 2002, Cambridge, MA, USA.
[7] Centro Astronómico de Yebes. Guadalajara, Spain.
[8] A.Kerr, S-K.Pan, J.E.Effland, "Sideband Calibration of Millimeter-Wave Receivers", ALMA Memo

#357, March 27, 2001.