# A High-Performance 650 GHz Sideband-Separating Mixer — Design and Results

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***Abstract*—We designed, built and tested a new sideband-separating mixer assembly for the 600–720 GHz band (ALMA Band 9). By concentrating on the input matching and isolation of the quadrature hybrid and associated waveguide components, rather than on the phase and amplitude balance, we minimized standing waves and especially asymmetric reflection paths, which are highly detrimental to the image rejection ratio (IRR). IRRs in excess of 15 dB are obtained repeatably with different blocks and mixer pairs. At the same time, the SSB noise temperature is increased by not more than 20–30 K with respect to the bare mixer devices, corresponding to a loss of about 0.5 dB in the waveguide structure. A considerable contribution to the IRR are reflections in the IF system. If these are eliminated, *i.e.*, by using highly matched IF amplifiers, we expect worst-case IRRs of 18 dB or better can be reached, even in array configurations. In less demanding cases, the ample margin in IRR on the RF side can be used to build a system with reasonably matched amplifiers that still meets a typical 10 dB IRR specification. These 2SB mixers are intended for future sideband-separating receivers on the APEX (Chile) and LLAMA (Argentina) observatories and for deployment in any other observatory that would benefit from sideband separation in the 600–720 GHz band.**

## I. Introduction

A new waveguide structure for a 600–720 GHz sideband-separating (2SB) mixer was recently presented [1], based on all our findings with the previous generation modular Band 9 2SB mixer [2], [3]. The waveguide structure follows the classical quadrature hybrid architecture, micromachined together with LO couplers and an in-phase LO splitter into a modular waveguide split-block [4]. The mixer devices are the same superconductor-insulator-superconductor (SIS) devices used in the current ALMA Band 9 receivers. The waveguide losses observed in the preceding design were minimized by choosing the waveguide dimensions as large as possible compatible with single-moded operation ($400{\times}200\,\mu$m), and machining them out of low-loss copper-tellurium alloy without gold plating.

Detailed study [5] reveals that the main mechanisms limiting the image rejection ratio (IRR) are asymmetrical reflection paths inherent in the 2SB architecture. Two such paths exist (Fig. 1): 1) reflections from each SIS device that pass back through the hybrid to interfere constructively at the RF-load port, after which any reflection from the load is redistributed equally over the mixers; and 2) reflections from either SIS device to the other by taking a "U-turn" through the hybrid

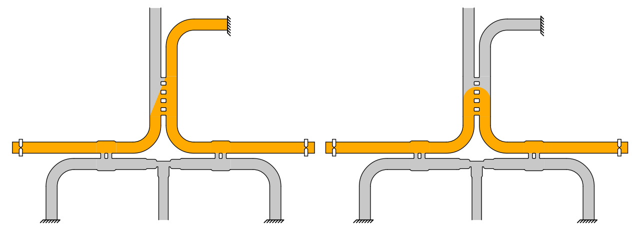

Fig. 1. The two reflection paths that cause most of the deterioration of the image rejection, when the contributions of the amplitude and phase balance are accounted for.

(corresponding to the hybrid's isolation parameter). Although the detailed accounting of $\pm 90^\circ$ phase shifts is different, the total effect is the same in both cases: whenever due to the overall phase rotation in the system the direct and reflected signals arrive in phase in one mixer, they are in precisely in anti-phase in the other, having a maximum detrimental effect on the the image rejection ratio. To optimize the IRR, both reflection paths were suppressed as much as possible, by improving the hybrid's idle port load, and by making the isolation of the hybrid one of its primary optimization goals.

## II. Hybrid design

Fig. 2 shows a representative set of simulated S-parameters for the hybrid. The crucial isolation factor $|S_{21}|^2$ is below $-24$ dB within the band, considerably lower than in the previous design. At the same time, the gain and phase errors

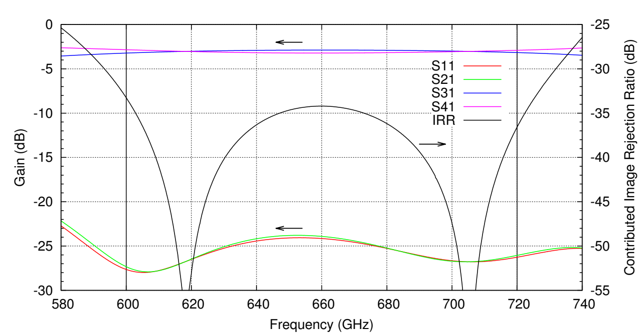


Fig. 2. Simulated S-parameters of the hybrid and the hybrid's contribution to the image rejection ratio ("IRR").

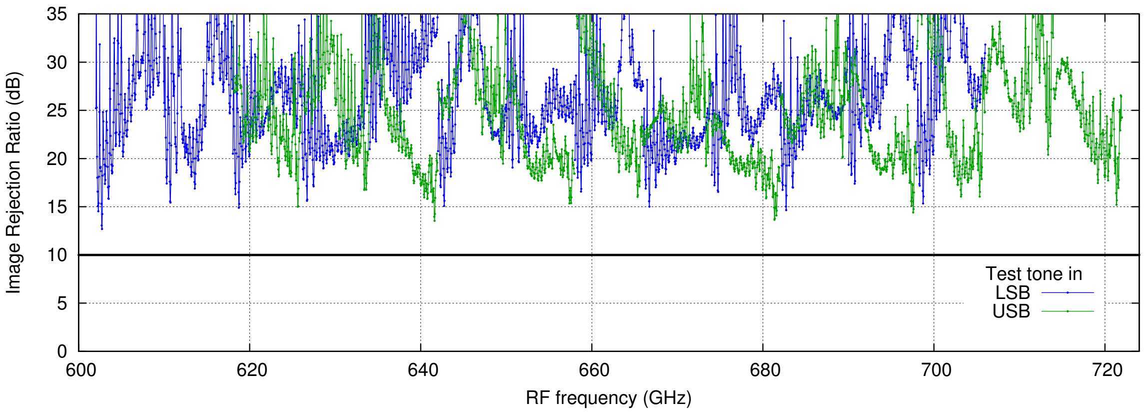


Fig. 3. Image rejection ration (IRR) of the first production hybrid block as function of RF observation frequency (*i.e.*, the frequency of the test tone used to determine the IRR). The typical specification for 2SB ALMA bands (10 dB minimum) is indicated with a horizontal line.

(not shown here) are within $\pm 0.4$ dB and $\pm 0.4°$, respectively. The hybrid's contribution to the IRR, derived from the $S$-parameters, is plotted as well. The worst-case point in the band is about -33 dB, which gives the upper limit for the overall image rejection possible with this design.

## III. Results

Fig. 3 shows the image rejection ratio obtained with one of the four production blocks. The IRR is above 15 dB in almost all points, with ample margin within the typical specification ($\geq$10 dB) of current receivers.

The single-sideband (SSB) noise temperature (Fig. 4), meets ALMA-class specifications with margin. To give an idea of the noise penalty incurred by the waveguide structures, the sum of the DSB noise temperatures of the individual mixer devices is plotted as well, showing an excess of about 20 K, corresponding to about 0.5 dB loss in the waveguide structure.

About a dozen different pairs of SIS mixers were tested. Most were chosen to match gain and normal-state resistance $R_N$ as closely as possible, but some were mismatched on purpose. However, no simple correlation between the mixer gains as determined in DSB measurements (nor normal-state resistance $R_N$, noise temperature $T_n$ or pumping current) and the obtained IRRs was observed. Geometrical proximity on the production wafer seemed to be the best predictor for high IRR, possibly due to gradients in the $SiO_2$ dielectric modifying the phase relations of the on-chip filter structures.

Apart from large-scale (order 10 GHz) patterns in the IRR resulting from residual imbalances in the RF circuit, there are persistent small-scale (sub-GHz) ripples, attributable to the IF system. Classically, IF ripples are suppressed by inserting isolators between the mixers and the LNAs. For 4-channel 4–12 GHz ALMA-style receivers, or small multipixel arrays, this becomes unpractical. In a simple experiment, where we removed the isolators from the IF chain and used MMIC LNAs with improved input reflection ($\leq -7$ dB), the worst-case IRR is reduced by about 5 dB, making it touch the typical 10 dB specification, while the noise temperature was reduced by about

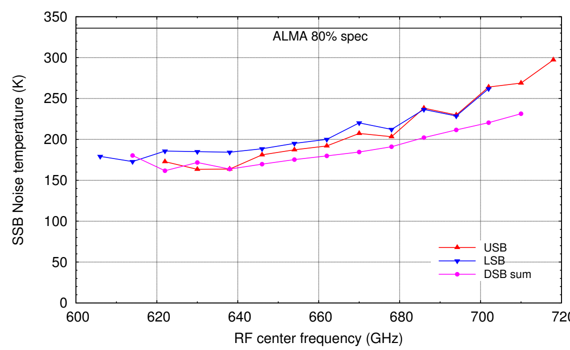


Fig. 4. Single-sideband noise temperature of both upper and lower sidebands as function of the RF frequency, as well as the sum of the DSB noise temperatures of the two individual SIS mixer devices.

10 K. The observed deterioration of the IRR is not simply due to standing waves, but probably to similar unbalanced interference effects as in the RF circuits.

## References

[1] R. Hesper, A. Khudchenko, A. M. Baryshev, J. Barkhof, and F. P. Mena, "A new high-performance sideband-separating mixer for 650GHz," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 9914, 2016, pp. 99 140G–99 140G–11. [Online]. Available: http://dx.doi.org/10.1117/12.2233065

[2] A. Khudchenko, R. Hesper, A. Baryshev, F. P. Mena, G. Gerlofma, T. Zijlstra, T. M. Klapwijk, J. W. Kooi, and M. Spaans, "First results of the sideband-separating mixer for alma band 9 upgrade," in *Twenty-Second International Symposium on Space Terahertz Technology, Charlottesville*, 2011, pp. 143–149.

[3] A. Khudchenko, R. Hesper, A. Baryshev, G. Gerlofma, J. Barkhof, J. Adema, P. Mena, T. Klapwijk, and M. Spaans, "Sideband separating mixer for 600-720 ghz for alma band 9 upgrade," in *Society of Photo-Optical Instrumentation Engineers (SPIE) Conference Series*, vol. 8452, sep 2012, p. 14.

[4] R. Hesper, G. Gerlofsma, F. P. Mena, M. C. Spaans, and A. M. Baryshev, "A sideband-separating mixer upgrade for alma band 9," in *Twentieth International Symposium on Space Terahertz Technology, Charlottesville*, apr 2009, pp. 257–260.

[5] A. Khudchenko, R. Hesper, A. M. Baryshev, J. Barkhof, and F. P. Mena, "Modular 2sb sis receiver for 600–720 ghz: Performance and characterization methods," *IEEE Transactions on Terahertz Science and Technology*, vol. PP, no. 99, pp. 1–8, 2016.