Fully integrated sideband-separating Mixers for the NOEMA receivers

D. Maier, J. Reverdy, L. Coutanson, D. Billon-Pierron, C. Boucher and A. Barbier

Abstract—**Sideband-separating mixers with wide IF band have been developed for the NOrthern Extended Millimeter Array. The development of a planar IF coupler chip made it possible to design fully integrated sideband-separating mixers for two of the four bands of the interferometer.**

Index Terms—**Superconductor-insulator-superconductor (SIS) mixer, sideband-separating mixer, integrated mixer, wide IF band**

I. INTRODUCTION

THE Plateau de Bure observatory run by the Institut de RadioAstronomie Millimétrique in the French Alpes will be upgraded during the next years to become the **NO**rthern **E**xtended **M**illimeter **A**rray (NOEMA). This largest millimeter project in the northern hemisphere consists of doubling the number of antennas from six to twelve, extending the baseline and installing new state-of-the-art dual polarization receivers with four frequency bands, providing each two approximately 8 GHz wide IF bands per polarization by employing sideband separating mixers. Table 1 gives an overview over the four frequency bands of the new NOEMA receivers compared to the current PdBI receivers.

Table 1: Comparison of the four frequency bands of the NOEMA receivers and the PdBI receivers.

	PdBI			NOEMA		
Band	**Fr. range [GHz]**	**Mix. type**	**IF Band [GHz]**	**Fr. range [GHz]**	**Mix. type**	**IF Band [GHz]**
1	83–116	SSB	4–8	72–116	2SB	3.872–11.616
2	129–174	SSB	4–8	129–179	2SB	3.872–11.616
3	200–268	SSB	4–8	200–276	2SB	3.872–11.616
4	277–371	1SB	4–8	275–373	2SB	3.872–11.616

Because of the atmospheric conditions on-site, Band 4 is of lowest priority for the project, so that in a first phase no new development will be started for this band. Instead the current PdBI mixers will be used. These are sideband-separating mixers with an IF band of 4-8 GHz initially developed for the ALMA Band 7 cartridge [1], but with only one IF output being further processed.

Bands 1 to 3 however will make use of IRAM's more recent mixer developments consisting of sideband-separating mixers with wide IF band. Bands 1 and 2 will even be equipped with fully-integrated sideband-separating mixers.

Manuscript received June 13, 2014. This work was supported in part by the European Union through the Radionet program.

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II. IF COUPLER CHIP FOR 2SB MIXERS

Sideband-separating SIS mixers are nowadays commonly used in radioastronomical receivers, in order to suppress atmospheric noise in the image band. Most of these mixers use waveguide structures for the realization of the 90º RF coupler, the LO couplers and the in-phase LO splitter, which allows these elements to be integrated together with the two DSB mixers into one E-plane splitblock. The 90º IF coupler on the other hand has not yet been integrated with the RF components, but is still a stand-alone unit in today's mixers, regardless whether a commercially available or a custom-made coupler is used. Mostly these couplers are based on nonhomogeneous dielectric broadside coupled striplines, which makes it impossible to integrate them into the commonly used E-plane splitblock.

Therefore we developed a completely planar IF coupler chip. It makes use of Nb striplines deposited onto a quartz substrate. In order to achieve a very low gain imbalance over the whole IF band of 4 to 12 GHz, three coupling sections are employed. The middle section consists of a Lange-type coupler, where the classically used bonding wires have been replaced by microstrip bridges separated from the underlying Nb lines by an SiO_2 layer. This Lange coupler is inserted between two sections of coupled microstrip lines as can be seen from the schematical layout shown in Fig. 1.

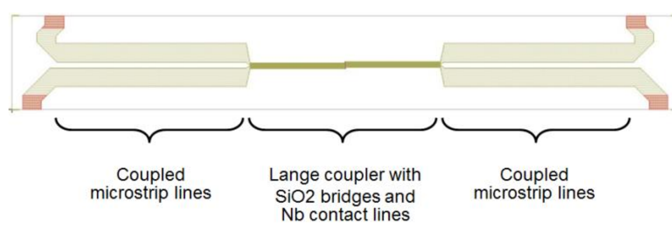

Fig. 1. Layout of the IF coupler chip.

The coupling sections have been optimized using Sonnet [2] yielding 20 μm and 10 μm for the finger width and spacing of the Lange coupler, respectively, and 540 μm and 160 μm for the width and the spacing of the coupled lines, respectively. The lengths of the coupling sections are each 5.49 mm. The distance between the two inputs of the chip have been matched to the distance between the two IF outputs of our existing 230 GHz 2SB mixer (see below), i.e. 16.7 mm, whereas the pitch of the two outputs had been chosen to be 18 mm to provide enough space for the IF amplifiers to be connected directly to the IF coupler.

The simulation results of the coupler chip are shown in Fig. 2. The gain and phase imbalances of the optimized chip are better than ±0.3 dB and 1º, respectively, and both input reflection and isolation are better than –20 dB.

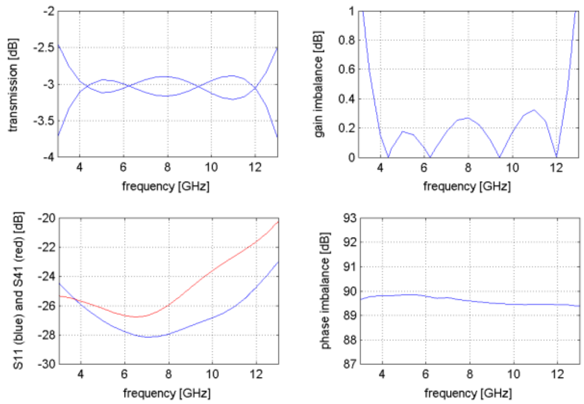

Fig. 2. Simulated performance of the IF coupler chip.

III. Band 3 mixer

The newly developed IF coupler has been tested with our 230 GHz 2SB mixer developed within the European project AMSTAR+ [3], [4] and installed since autumn 2011 in EMIR (**E**ight **MI**xer **R**eceiver), the receiver of IRAM's 30m antenna at Pico Veleta in Spain [5]. A photograph of one half of the E-plane splitblock of this mixer is shown in Fig. 3 on the left-hand side. With this mixer the coupler is used as a standalone unit in a dedicated housing (see Fig. 3, right). It replaces the so far used IF coupler based on nonhomogeneous dielectric broadside coupled striplines and developed for the use at cryogenic temperatures [6].

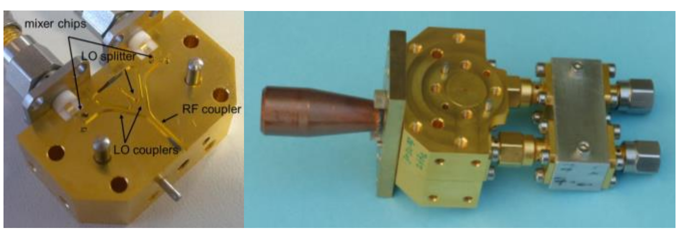

Fig. 3. Left: Photo of one half of the E-plane splitblock of the Band 3 sideband-separating mixer integrating RF coupler, LO splitter, LO couplers and DSB mixers. Right: Complete 230 GHz 2SB mixer with newly developed IF coupler.

The 2SB mixer has been fully characterized by measuring its noise temperatures and image rejections in an IF band of 3.8 to 12 GHz with steps of 100 MHz and for LO frequencies between 210 and 270 GHz. The results are shown in the plots in Fig. 4. The obtained noise temperatures lie approximately between 40 and 60 K over the whole band of 200 to 268 GHz and the image rejections are almost always better than -10 dB with an average value around -18 dB.

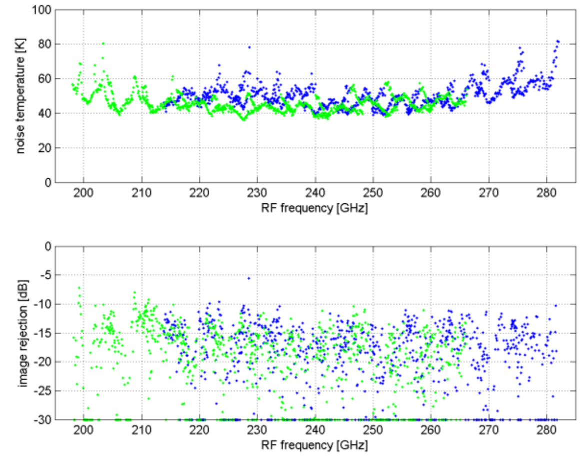

Fig. 4. Measurement results of the 230 GHz 2SB mixer. Above: Noise temperatures as a function of the RF frequency. Below: Image rejections as a function of the RF frequency. LSB measurements are shown in green, USB measurements are plotted in blue.

IV. Band 2 Mixer

So far only backshort tuned single sideband mixers have been employed at IRAM in this frequency range [7]. Therefore a completely new sideband-separating mixer had to be designed for the NOEMA receivers.

A. *2SB mixer assembly*

A coupler/mixer block integrating now not only RF coupler, LO splitter, LO couplers and DSB mixer blocks, but also the IF coupler has been designed as an E-plane splitblock (see Fig. 5). All RF components of this block have been optimized using CST Microwave Studio [8]. The results are shown in Fig. 6-Fig. 8.

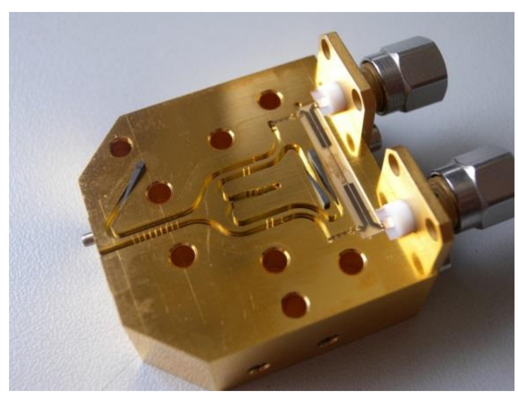

Fig. 5. One half of the E-plane splitblock of the Band 2 sideband-separating mixer.

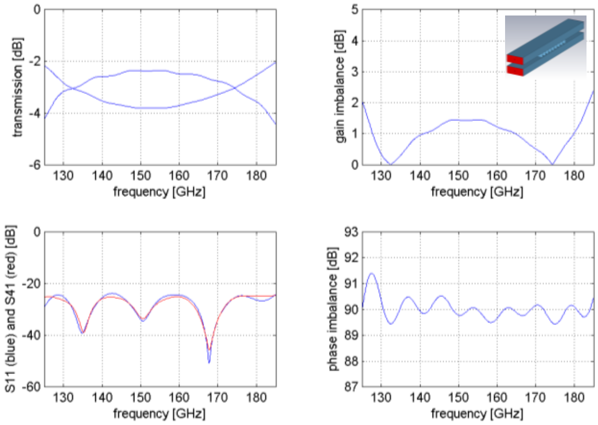

Fig. 6. Simulated performance of the Band 2 90º rf coupler.

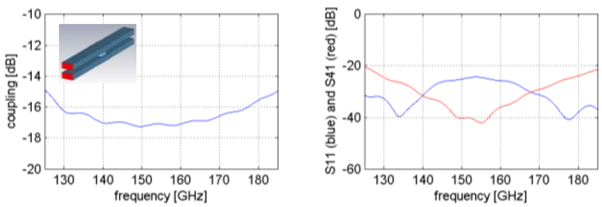

Fig. 7. Simulated performance of the Band 2 LO coupler.

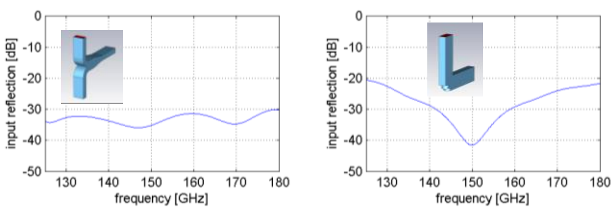

Fig. 8. Simulated performances of the Band 2 in-phase LO splitter (left) and the h-plane bend (right).

B. *DSB Mixer*

The DSB mixer employs superconductor-insulator-superconductor (SIS) tunnel junctions integrated in a superconducting circuit on a quartz substrate. The layout of one individual mixer chip with a size of 0.4 x 3.5 x 0.08 mm^3 is shown in Fig. 9. These devices are fabricated by IRAM's SIS group [9], [10].

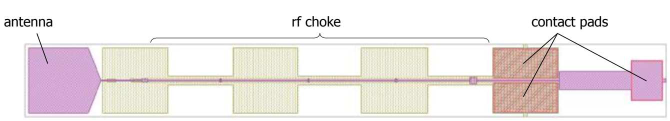

Fig. 9. Layout of the Band 2 mixer chip.

The mixer chip is placed in a channel perpendicular to the waveguide axis and stretches partly across the waveguide as shown in Fig. 10, left. The incoming radiation is coupled to the chip through a full-height waveguide to microstrip transition consisting of a suspended stripline structure at the end of the chip (see Fig. 9 on the left). This structure has been optimized using CST Microwave Studio [8] resulting in a slightly capacitive antenna impedance of around 50 Ω shown in the Smith chart in Fig. 10 on the right.

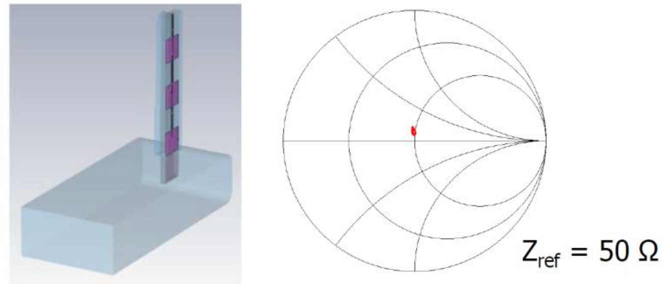

Fig. 10. Full-height waveguide to microstrip transition. Left: Mixer chip placed in the waveguide. Right: Antenna impedance for frequencies between 129 and 179 GHz.

The mixing element consists of a series array of three Nb-Al/AlOx-Nb junctions, each junction having an area of 1.7 x 1.7 µm^2 and the normal state resistance of the array being 20 Ω. Two of the three junctions are placed on an island structure as shown in Fig. 11 on the right-hand side, which adds a small series inductance to the capacitive junction array. The residual capacitance of the structure is tuned out by means of a parallel inductance realized as coplanar waveguide followed by a large capacitance providing a virtual ground for RF frequencies (see Fig. 11, left, and Fig. 12). Behind the capacitance, the rf choke consisting of alternating coplanar waveguide sections and capacitances blocks the rf signals and only lets pass the IF signal. The circuit is completed by the λ/4-wavelength transformer which matches the impedance of the junction array with its tuning structure to the antenna impedance shown in Fig. 10 on the right.

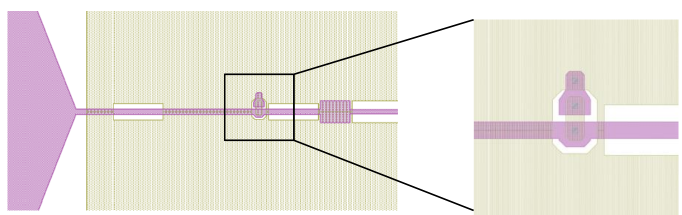

Fig. 11. Tuning structure and SIS junction array.

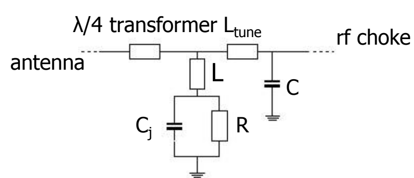

Fig. 12. Schematic view of the tuning structure.

The achieved embedding impedance of the junction is shown in the Smith chart in Fig. 13, left, for frequencies between 129 and 179 GHz. It is quite close to the junction's RF impedance, so that the achieved coupling to the junction is better than 98% (see Fig. 13, right).

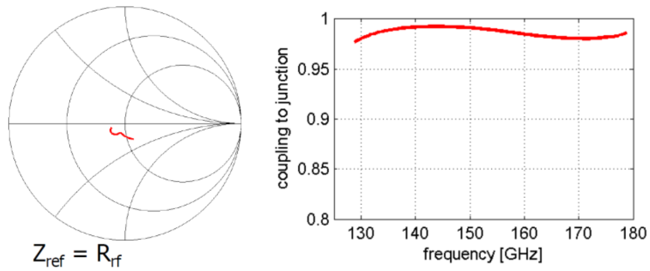

Fig. 13. Left: Embedding impedance of the junction for frequencies between 129 and 179 GHz. The Smith chart has been normalized to the junction's RF impedance. Right: The coupling to the junction is better than 98%.

C. *Measurement results*

Characterization of the fully integrated sideband-separating mixer showed very good performances with noise temperatures between 30 and 50 K over the whole band of 129 to 179 GHz and image rejections around -15 dB with only a few points lying above -10 dB. The obtained noise temperatures and image rejections measured in the IF band of 3.8 to 12 GHz with steps of 100 MHz and for LO frequencies between 134 and 174 GHz are shown in Fig. 14.

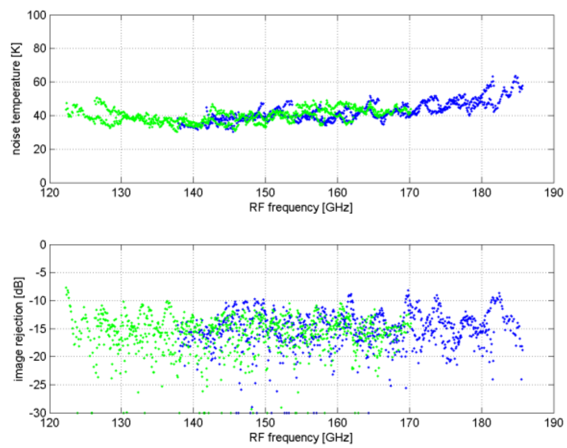

Fig. 14. Measurement results of the fully integrated 150 GHz 2SB mixer. Above: Noise temperatures as a function of the RF frequency. Below: Image rejections as a function of the RF frequency. LSB measurements are shown in green, USB measurements are plotted in blue.

V. Band 1 Mixer

The NOEMA Band 1 sideband-separating mixer is a further development of the 100 GHz mixer employed in EMIR (Eight Mixer Receiver) at IRAM's 30 m antenna at Pico Veleta [11], [12]. Just as for the Band 2 2SB mixer the RF coupler, LO splitter, LO couplers, both DSB mixers and the IF coupler have been integrated into one unit and realized as an E-plane splitblock. And since the frequency range has been expanded, now starting at 72 GHz compared to formerly 82 GHz, all RF waveguide components have been redesigned to account for this new frequency range using CST Microwave Studio [8]. The simulated performances of these components are shown in Fig. 15-Fig. 17.

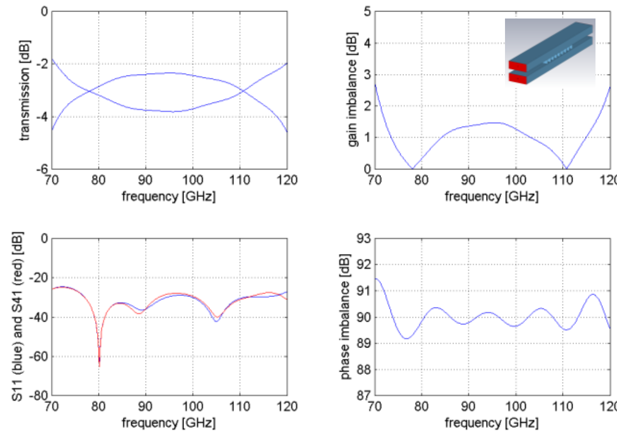

Fig. 15. Simulated performance of the Band 1 90º rf coupler.

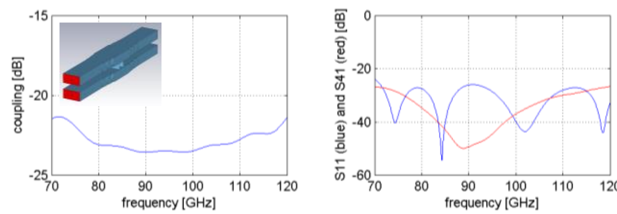

Fig. 16. Simulated performance of the Band 1 LO coupler.

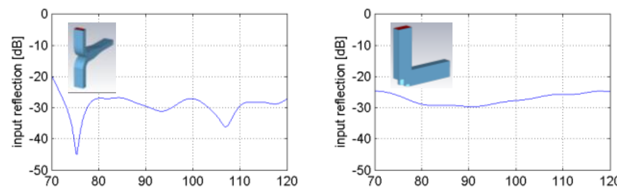

Fig. 17. Simulated performances of the Band 1 in-phase LO splitter (left) and the h-plane bend (right).

However, simulations of the mixer chip showed that it should work down to 72 GHz, so that no new mixer design was necessary.

One half of the E-plane splitblock of the new Band 1 mixer with mounted mixer chips, IF coupler and waveguide loads is shown in Fig. 18.

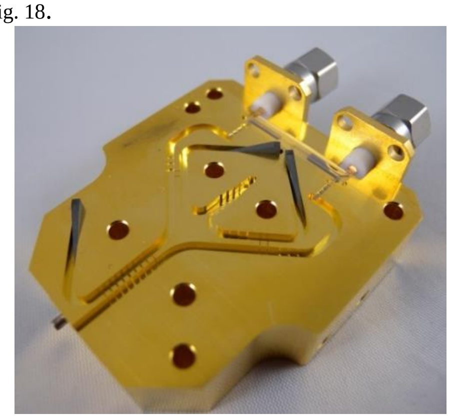

Fig. 18. One half of the E-plane splitblock of the Band 1 sideband-separating mixer.

Tests of the new fully-integrated 100 GHz sideband-separating mixer showed not only very good performances of noise temperatures around 30 K and image rejections around -15 dB over the extended frequency range of 72-116 GHz (see Fig. 19), but also that the mixer can indeed operate for frequencies between 70 and 122 GHz, i.e. it has a bandwidth of around 55 %.

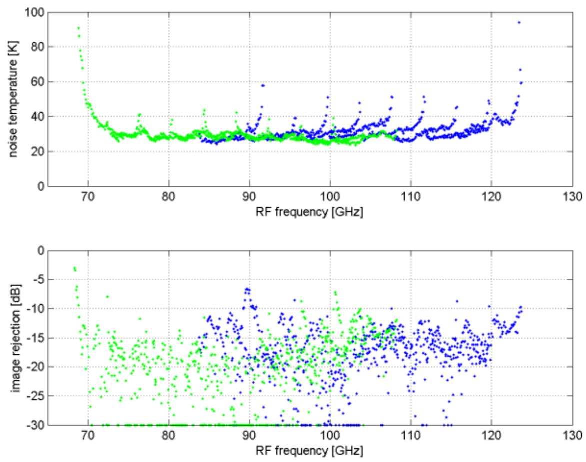

Fig. 19. Measurement results of the fully integrated 100 GHz sideband-separating mixer. Above: Noise temperatures as a function of the RF frequency. Below: Image rejections as a function of the RF frequency. LSB measurements are shown in green, USB measurements are plotted in blue.

VI. Conclusions

Wide-IF band sideband-separating mixers have been developed for the Bands 1 to 3 of the NOEMA receivers. The development of a planar IF coupler chip made it possible to design fully-integrated sideband-separating mixers for Bands 1 and 2. All mixers show state-of-the-art performances with very good noise temperatures and image rejections around -15 dB.

The first new NOEMA antenna equipped with these developments will be delivered in autumn 2014.

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