H2020 Grant Agreement No. 730562 – RadioNet

PROJECT TITLE:	Advanced Radio Astronomy in Europe
STARTING DATE	01/01/2017
DURATION:	48 months
CALL IDENTIFIER:	H2020-INFRAIA-2016-1
TOPIC:	INFRAIA-01-2016-2017 Integrating Activities for Advanced Communities

Deliverable 5.4

Very wideband RF/IF SIS receiver Design and test report on prototype wideband mixer built on 2SB technology and operating around 1-mm

Due date of deliverable:	2020-12-31
Actual submission date:	2020-12-30
Leading Partner:	CHALMERS TEKNISKA HOEGSKOLA AB (OSO)

Document information

Document name:	Very wideband RF/IF SIS receiver Design and test report on prototype wideband mixer built on 2SB technology and operating around 1-mm
Type	Report
WP	WP5 – AETHRA
Version date:	2020-12-30
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Dissemination Level

Dissemination Level		
PU	Public	X
PP	Restricted to other programme participants (including the Commission Services)	
RE	Restricted to a group specified by the consortium (including the Commission Services)	
CO	Confidential, only for members of the consortium (including the Commission Services)	

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RadioNet has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 730562

COVID-19 affects the Deliverable D5.4, to which the Art.51 applies as follows: A 2SB SIS junction mixer operating at 1mm and with wide IF band has been built and successfully tested on the sky at the APEX telescope, as originally aimed. However, the additional originally planned design of an RF wideband 2SB was not possible to complete in time, as announced, discussed and agreed earlier. Therefore, we report on the partial technological results obtained towards the realization of a wide RF/IF mixer operating at 1 mm wavelength.

1 Executive Summary

The primary goal of the task is to develop novel technology to serve the need of the THz radio-astronomy community. The specific needs addressed in this task are possible widening of the RF and IF bandwidths of SIS mixers operating at about 300 GHz (1 mm wavelength). We first demonstrate the performance of a wide IF 2Sb SIS receiver on the APEX telescope. Furthermore, we report on the partial technological results obtained towards the realization of a wide RF/IF mixer operating at 1 mm wavelength in the form of the design, fabrication and characterisation of a wideband waveguide-to-substrate transition compatible with SIS mixers design at 1 mm wavelength.

2 Wide IF receiver operating at 1 mm: SEPIA 345

2.1 Cold Cartridge design

The SEPIA345 receiver is a dual polarization receiver, where each polarization employs a sideband separating mixers. The SEPIA345 cartridge receiver provides the ability to observe in one of the ten frequency bands of the ALMA Observatory (band 7), I.e. 272-376 GHz. It uses standard FE cartridge bodies of 170 mm in diameter and is designed to be installed in the SEPIA receiver [1] on the APEX telescope. The cartridge employs cold optics, a feedhorn, and a waveguide orthomode transducer (OMT) to separate signals with orthogonal linear polarizations, sideband separating (2SB), fixed tuned SIS mixers and cryogenic intermediate frequency (IF) amplifiers.

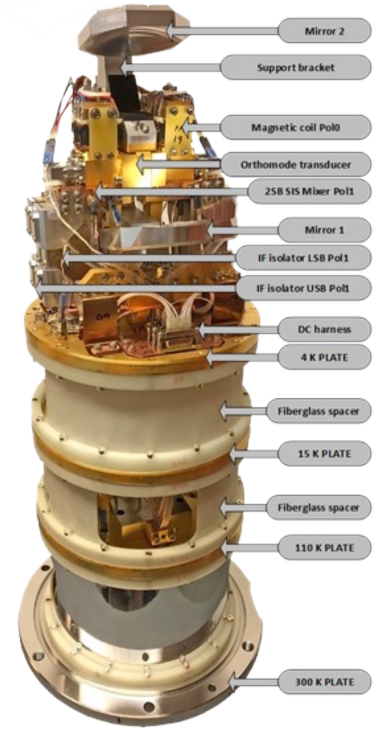

Fig. 2.1-1 Picture of the produced SEPIA345 cartridge

The signal enters the SEPIA receiver channel through the cold optics and after separation of polarizations via OMT is fed to the 2SB mixers. The two intermediate frequency (IF) outputs go through the final stage of the sideband separation in the IF hybrid and each, upper sideband (USB) and lower sideband (LSB) then amplified by low-noise cryogenic amplifiers (LNAs), preceded by isolators. The IF bandwidth is 4–12 GHz for both the USB and LSB and for both polarizations, giving 32 GHz IF bandwidth with the capability to measure full polarization. The reference LO signal is generated by the warm cartridge assembly (WCA, not shown in Fig. 2.1-1) similar to the one of ALMA band7 receivers [2], multiplied x3 by the polarization-dedicated tripplers installed at 110 K and further guided to the 2SB SIS mixers installed at the 4 K cartridge thermal plate. The DC bias electronics (frontend bias module) is hosted by the WCA, outside the CCA.

As in most modern dual polarization receiver, A OMT is used to separate signals with orthogonal linear polarizations. The OMT design was inspired by the ALMA Band5 OMT [3]. The OMT outputs with Pol0 and Pol1 signals were placed at the opposite sides of the Band 5 OMT block. The opposite position of the OMT outputs in combination with 90-degree waveguide twist at one of the OMT outputs allowed the use of identical 2SB mixer assemblies for each polarization yielding a very compact mixer assembly layout and facilitating production.

Each of the two 2SB mixer assemblies uses a split block configuration (Fig 2.1-2). As mixer elements, Nb-AlxO-Nb SIS mixers, fabricated in-house [4], are employed. The receiver topology features, inside the mixer block, an input 3dB waveguide 90 degrees RF hybrid, SIS mixers along with output 90 degrees 3dB IF hybrid with integrated broadband impedance transformers and bias-T. In order to improve the side-band rejection of the SEPIA345 mixers) and a wide IF band (4-12 GHz) the whole IF circuitry is integrated on a single alumina chip comprising impedance transformers, biasTs and IF couplers. The local oscillator (LO) power is injected to the mixers by integrated -18 dB.

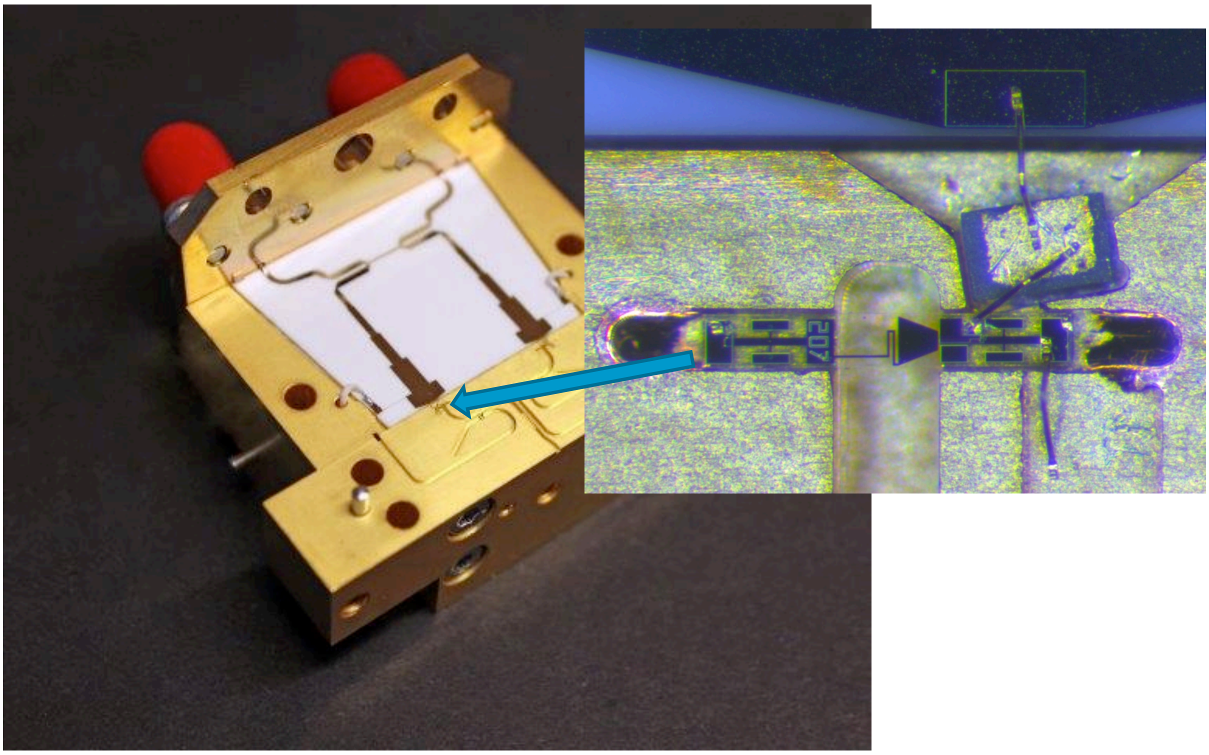

Fig. 2.1-2 SEPIA345 mixer block

2.2 Performance on Telescope

The receiver was assembled and installed in the SEPIA cryostat on the APEX telescope and is referred as the SEPIA345 channel/receiver in the beginning of 2020 and its commissioning was conducted under 2020. The noise performance of the receiver, sideband rejections of the receivers were measured on telescope and are presented in Fig. 2.2-1 and Fig.2.2-2 respectively.

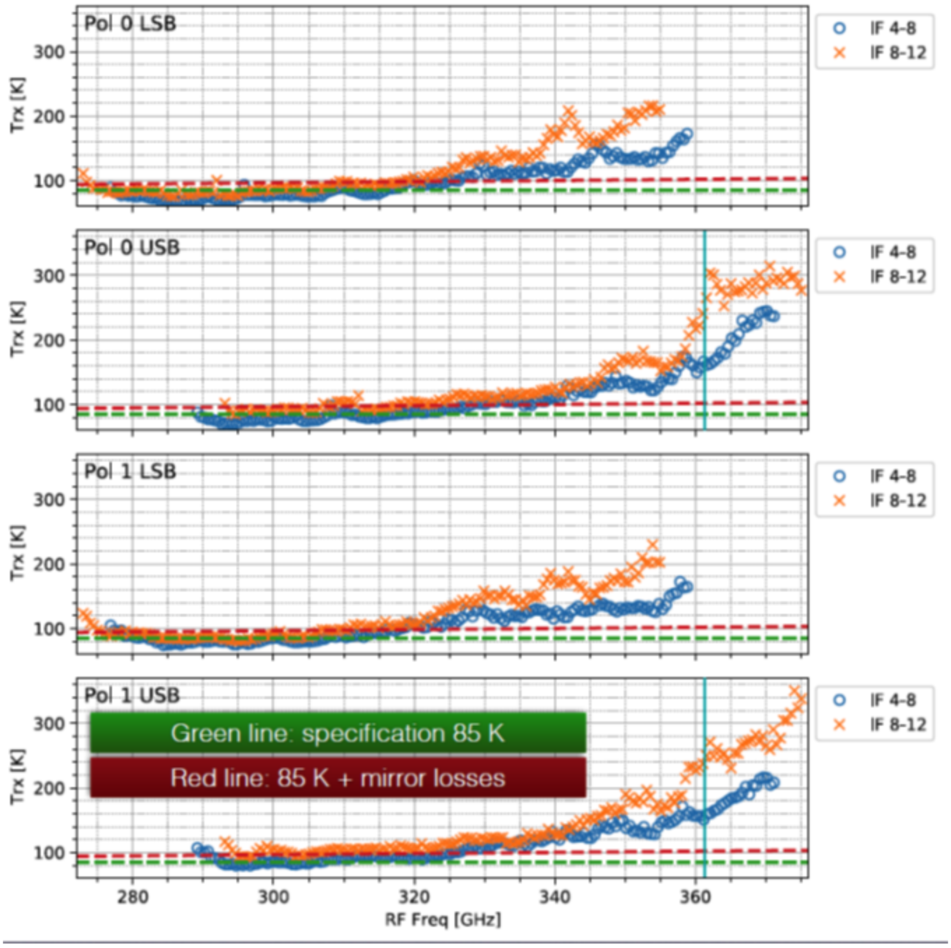

Fig. 2.22-1 Noise temperature of the SEPIA 345 for all sidebands.

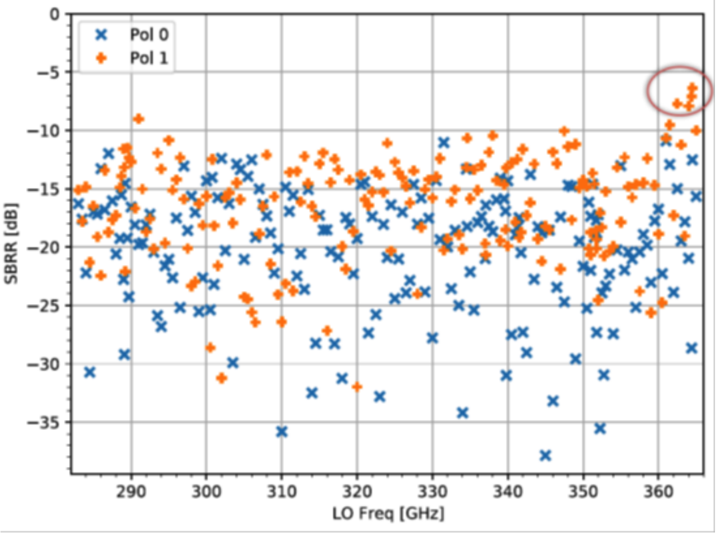

Fig. 2.22-2 Sideband rejection ratio for both polarizations.

Astronomical measurements at CO (3-2) frequencies were conducted and demonstrated the suitability of the receiver for such observations, recording sideband separation ratios from 12 dB to 22 dB (Fig 2.2-3).

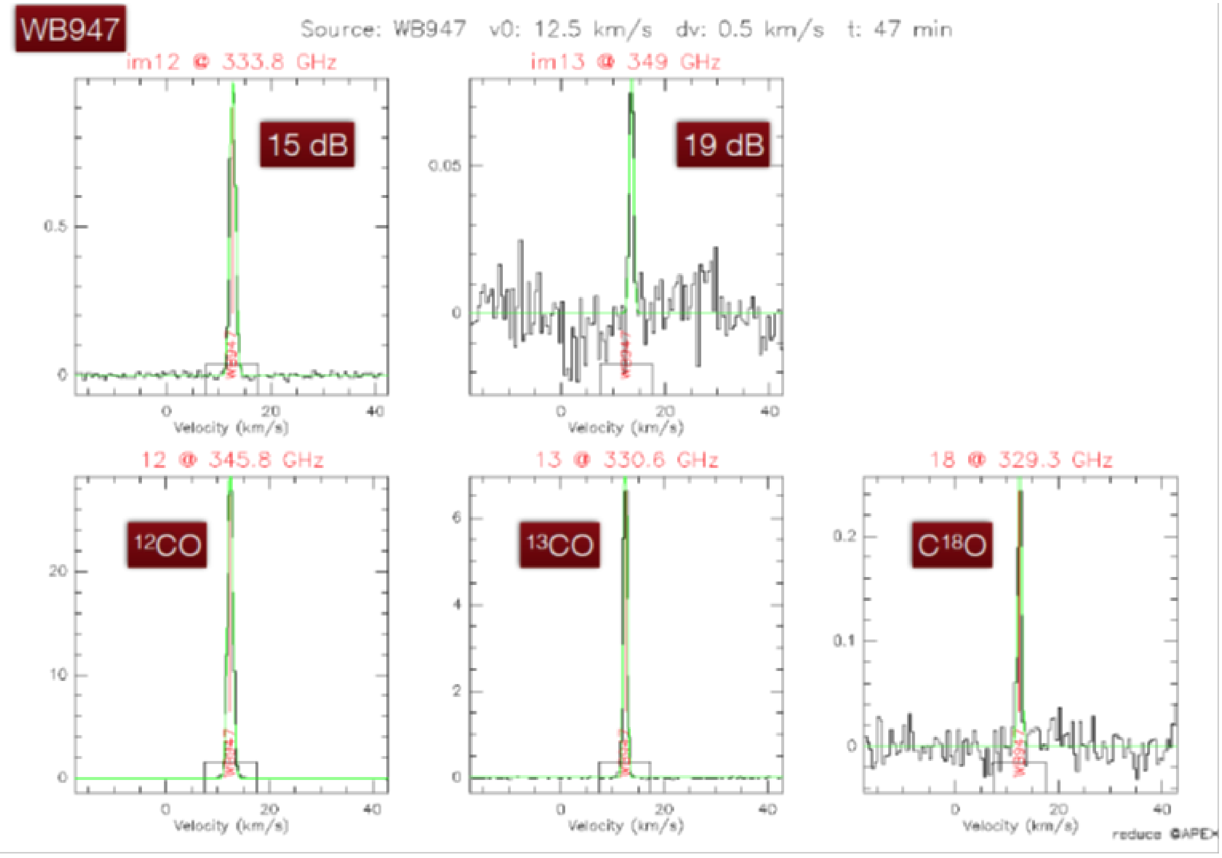

Fig. 2.22-3 Astronomical measurements at CO (3-2) frequencies with SEPIA 345.

Furthermore, the stability was assessed using Allan variance measurements at 345 GHz and show Allan times larger than 100 s, well above the specification (Fig.2.2-4)

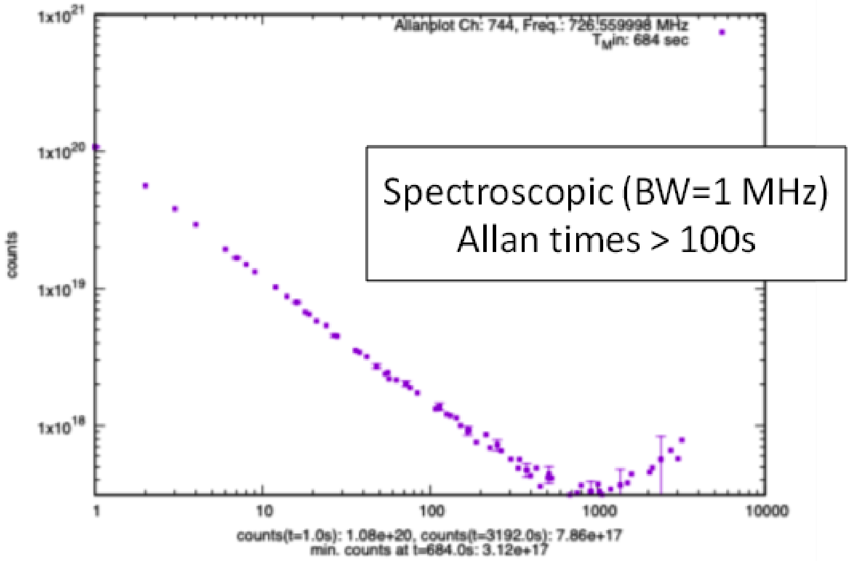

Fig. 2.22-4 Spectroscopic Allan variance at 345 GHz.

The functionality of the receiver was acknowledged and the receiver with wide IF bandwidth (4-12 GHz) is now open for science observations.

3 Towards wide RF/IF receiver operating at 1 mm.

3.1 Descoping

GARD possibilities to fully complete the second part of the D.5.4. was seriously affected by COVID-19 pandemic, as mentioned in earlier communication within the JRA and hence its suggested de-scoping. Reduced or banned access to measurement labs and clean room facilities practically severely limited our progress in the designing, fabrication and testing wide-RF mixer chip. Despite this constrains, GARD managed, on the communicated best-effort basis, to manufacture the demonstrator of the ultra-wideband waveguide-to-chip RF transition and even characterize it at cryogenic temperatures. The results correspond to our expectations from the modelling and are very promising. This gives good hope that this work will be used in planned future wide-RF mixer chip. At his moment, we have to declare that we are not capable to complete the tests of the mixer chip because of COVID-19 circumstances

3.2 Wideband waveguide to substrate transition

The first step to improve the RF bandwidth of a mixer is to design a wideband waveguide to substrate transition. Bearing in mind standard SIS mixers and their typical impedances, it practically means that the matching between the high impedance of the full-height waveguide and a slotline is crucial. In this particular design it is accomplished in two stage layout. The first stage employs a unilateral finline structure, while a 2-section slotline Chebyshev transformer is implemented to finally reach the desired slotline impedance of about 60 Ohm. In contrast to previous finline designs, we remove the dialectic material from the space between the fins to minimize reflection and dielectric material losses. The initial finline transition was designed using the Chebyshev transformer (stepped), which then was approximated by the smooth line-transition drawn through the middle of the Chebyshev transformer steps. This is illustrated in Fig. 3.2-1, left. Thereafter the resulting transition geometry was further optimized by simulation in the HFSS software. The entire transition was simulated and optimized using Ansys™ HFSS for waveguide dimensions 400x800 µm. Fig. 3.2-1 shows simulated performance of the back-to-back waveguide-finline-slotline-finline-waveguide transition.

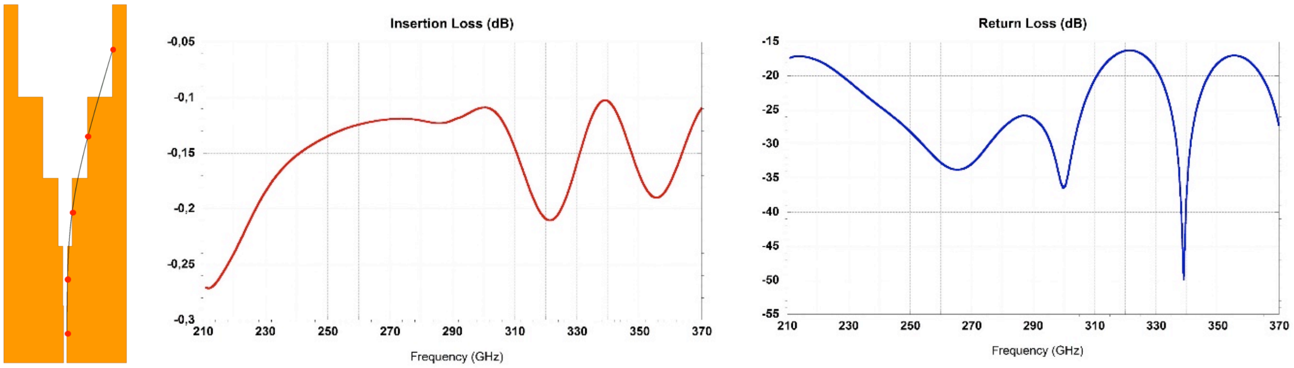

Fig. 3.2-1 From left to right. Layout of the finline transition showing the starting Chebyshev transformer steps and spline profile of the finline transition from the full-height waveguide to slotline with 60 Ohm impedance. 60 Ohm impedance gives slot-line geometry with reasonable dimensions (slot width) attainable by optical lithography. The plot to the middle shows the insertion loss of the back-to-back transitions. The plot to the right shows the return loss of the input/output ports.

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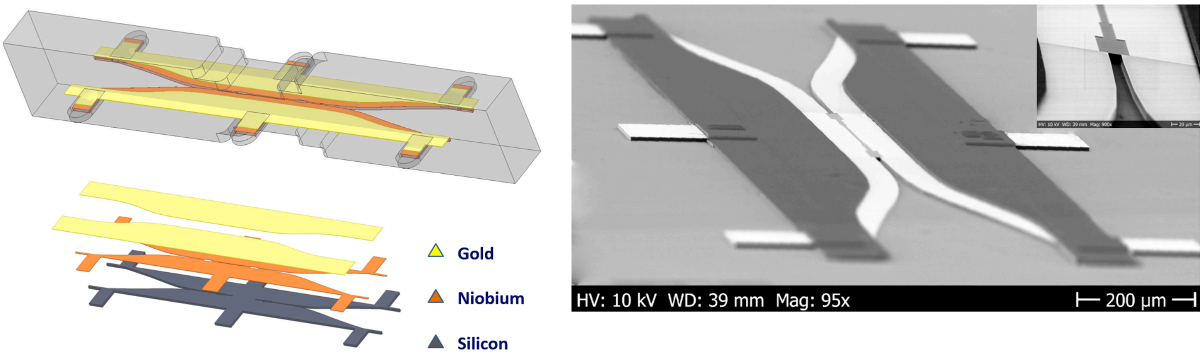

Fig. 3.2-2- From left to right. Integration of the finline back-to-back transition into the waveguide split block. The SEM picture of the fabricated structure.

For the technology verification purposes, a back-to-back transition was fabricated (Fig. 3.2-2). The transition is designed of a thin silicon substrate covered by a superconducting niobium thin layer. The substrate enclosed by the fins is completely etched in order to reduce the overall insertion loss and facilitate matching with the waveguide. An additional gold layer situated on top of the Nb-layer provides grounding for the fins and guarantees a simple mounting process in the split-block waveguide mount. Moreover, the waveguide width is gradually reduced in 2 steps to obtain a subcritical square cavity.

After completion of the simulations and optimizations, the waveguide block has been manufactured, the waveguide transitions have been fabricated allowing measuring the structure from 180 to 400 GHz in two bands with help of VNA extenders. The finline test structure has been fabricated (Fig. 3.2-3a-b) and mounted inside the waveguide block (Fig. 3.2-3c).

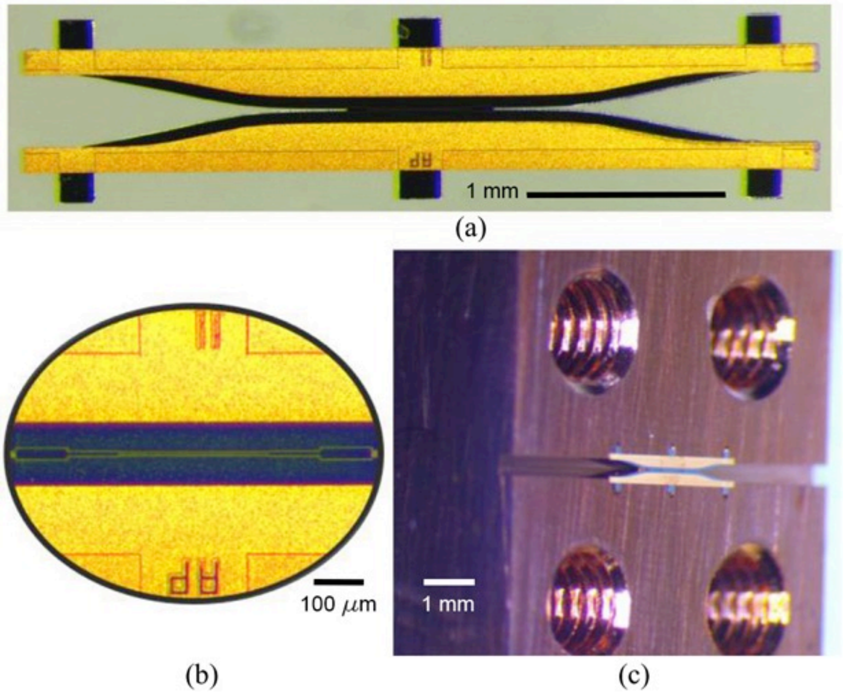

Fig. 3.2-3- From left to right. Integration of the finline back-to-back transition into the waveguide split block. The SEM picture of the fabricated structure.

The experimental verification [5] of the back-to-back structure was done in 4K in a cryostat. The S parameters were measured with a Keysight PNA-X 5242A and three VDI frequency extension modules, i.e., WR-5.1, WR-3.4, and WR-2.2. A standard TRL calibration was applied for the 220-330 GHz band at room temperature. This calibration was used for measuring the DUT at 4K. Moreover, a waveguide through with the same dimensions as the DUT block was measured at the same temperature. As the waveguide chain was identical for both measurements, the difference in the losses corresponds to the DUT. The measured and simulated insertion loss at 4K is depicted on the Figure 16. Compared to the presented on the Fig. 3.2-1, the simulation shown on the Fig. 3.2-4 accounts for the realistic (measured) conduction losses in the plated gold of the waveguide block and the transition chip, as well as the realistic dielectric losses in Si material used for the fabrication of the transition chip. From the Fig. 3.2-4, it can be concluded that measurements agree with the simulated data well.

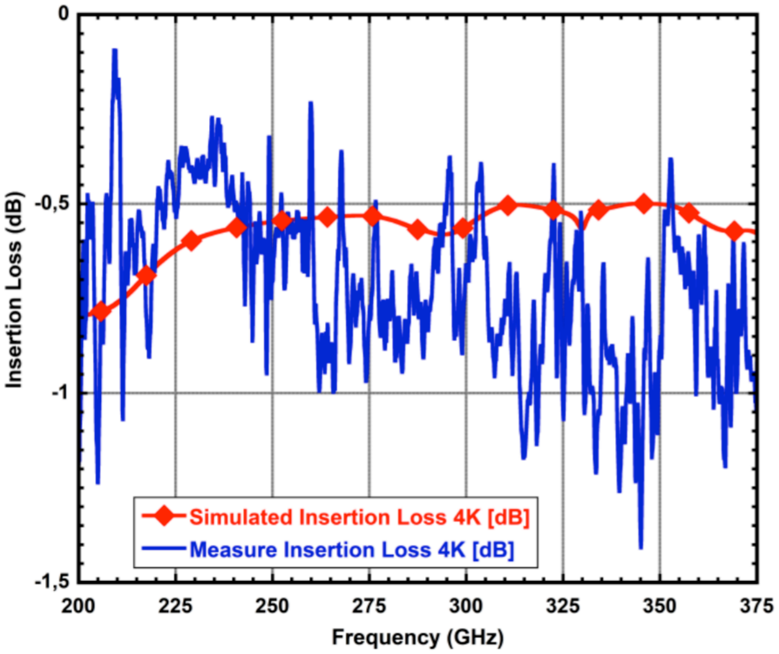

Fig. 3.2-4- After [5]: Relative measurement and simulation of back-to-back transition insertion loss at 4K.

The micromachined mixer chip designed and fabricated following the developed approach would allow easier mounting, low-inductance grounding and optimized IF circuitry likely integrated onto the mixer chip. This would provide promising technology to realize 2SB SIS mixer covering RF band 211-375 GHz with at least 4-12 GHz IF and largely suitable for production activities.

3.3 Future outlook.

Even though the AETHRA project formally finishes at the end of 2020, the work performed towards the realisation of a 2SB receiver with both wide RF and IF bands is likely to continue outside RadioNet with the remaining end-goal of going to the telescope again and being demonstrated there.

4 References

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[2] S. Mahieu *et al.*, “The ALMA Band-7 Cartridge”, IEEE trans. THz. Tech. vol 2, no. 1, 2012.

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