Compact Cryogenic Wide-Band Balanced Amplifiers with Superconducting 90° Hybrids for the IF of Submillimeter-Wave SIS Mixers

R. I. Amils, I. López-Fernández, J. D. Gallego, *Member, IEEE*, V. Desmaris, V. Belitsky, D. Meledin, E. Sundin, C. Diez, I. Malo

***Abstract*—The pressing demand for mm-wave cryogenic radio astronomy receivers with increasing instantaneous bandwidth has spurred interest in more complex intermediate frequency amplifier configurations, like the balanced amplifier, as the traditional options have increasing difficulties to comply either with the noise or the input matching specifications. This solution is typically penalized by the slight increment in noise produced by the quadrature hybrid losses. We propose a balanced amplifier using a novel 3 dB quadrature hybrid coupler design with superconducting lines. The prototype unit built for the 4-12 GHz band integrates in the same module the hybrid coupler chips, the low noise amplifiers and the bias circuitry. The mechanical design allows for an independent testing of the individual amplifiers. The average noise temperature is 4.4 K, only 0.3 K more than the average of its amplifiers. The input reflection improves more than 10 dB. This compact balanced amplifier is also compared with a non-integrated version, showing an improvement in noise and reflection. It has been tested in a complete mm-wave receiver, with advantage over other IF schemes.**

***Index Terms*—Cryogenic balanced amplifier, submillimeter wave receivers, superconducting hybrid coupler, low noise, radio astronomy.**

I. Introduction

THE new generations of THz receivers for radio astronomy demand increasingly wider instantaneous bandwidths [1], [2]. The requirements for the Intermediate Frequency (IF) cryogenic amplifiers are extremely difficult to meet, as larger fractional bandwidths force a trade-off between noise temperature and input reflection matching. The mismatch between the mixer, usually a superconducting-insulating-superconducting (SIS) junction and the low noise amplifier (LNA) poses many practical problems, like high ripples in the band or mixer instability. Two approaches to address this issue have been attempted in the past: (1) the use of input cryogenic isolators and (2) the implementation a balanced amplifier configuration. Both transfer the input reflection demands from the LNA to another additional component.

The first solution was employed, for example, in bands 5 and 9 of the Atacama Large Millimeter Array (ALMA) [3], which represent a standard for mm-wave receiver architectures. Its main disadvantages are, on the one hand, the insertion losses of the isolator, which could degrade the noise temperature by about 3 K for the 4-12 GHz ALMA band (at 15 K ambient temperature), and on the other hand, the limited fractional bandwidth of ferrite isolators. The performance of the available isolators in the ALMA band degrades at the edges, and it is very difficult to procure (or design) isolators for larger fractional bands.

The balanced solution is implemented in some radio astronomical receivers [4]. It is more cumbersome and expensive, as it requires two quadrature 3 dB cryogenic hybrid couplers and two LNAs. Although it suffers from the same loss problem, with a good hybrid design the results are better in noise (a penalty of 1.5 K in the aforementioned band) and reflection than with the input isolator. Moreover, the potential bandwidth is greater, making this solution expandable to future wider band receivers.

In this work, we propose using superconducting hybrid couplers [5] in the balanced amplifier to minimize the insertion losses and thus, the noise penalty of this configuration. Furthermore, we accomplish the integration of the pair of hybrids and amplifiers in the same block (what will be called henceforth a "compact balanced amplifier") in order to overcome the size drawback and to improve its matching and noise performance by eliminating the connectors between the balanced amplifier components.

The classical ALMA 4-12 GHz band, where adequate LNA and hybrid designs were already available, was selected for this implementation. Even though cryogenic amplifiers with acceptable input reflection levels have been recently developed for this band [6], the balanced configuration is superior in input matching, noise band ripple (due to the uncorrelation between input and output noise waves, see [4]), redundancy against failures in the field and even linear dynamic range. These advantages are increasingly determining

The work done at Yebes Observatory was supported in part by the European Union's Horizon 2020 research and innovation programme under grant agreement 73562 (RadioNet).

R. I. Amils, I. López-Fernández, J. D. Gallego and C. Diez are with Observatorio de Yebes, Centro de Desarrollos Tecnológicos del Instituto Geográfico Nacional (IGN), 19141 Yebes, Spain (e-mail i.lopez@gmail.com).

V. Desmaris, V. Belitsky, D. Meledin and E. Sundin are is with the Group for Advanced Receiver Development (GARD) of Chalmers University of Technology, SE-412 96 Gothenburg, Sweden (e-mail: vincent.desmaris@chalmers.se).

as the fractional bandwidth is further expanded.

The characteristics of the LNAs and the quadrature hybrids used are analyzed in sections II and III. The balanced amplifiers are presented in section IV. A first non-compact (modular) approach was assembled and tested, both in the labs and in a complete receiver with promising results. Finally, a prototype of a compact balanced amplifier was demonstrated. The measurement system and the results are analyzed in sections V and VI.

II. Low Noise Amplifiers

The low noise amplifiers used for this work are based on the well stablished design used in the 4-12 GHz IF of ALMA bands 5 and 9. A description can be found in [3]. It is implemented in microstrip hybrid technology, with single chip transistors for each of the three stages. For this application, InP HEMT devices were placed in all stages to optimize noise and reduce power consumption. In particular, the first stage input network was tuned to fit a 150 × 0.1 µm gate Diramics[1] transistor with state-of-the-art noise performance, developed in collaboration with ETH[2] (see Fig. 1). The original ALMA design was conceived to be used in combination with a cryogenic input isolator, hence no effort was put on the optimization of the input return losses, which makes it an excellent candidate to test the benefits a balanced configuration.

The LNAs used in the balanced amplifier yield a noise temperature around 4 K (measured at 5 K ambient temperature). Their performances are given in section V.

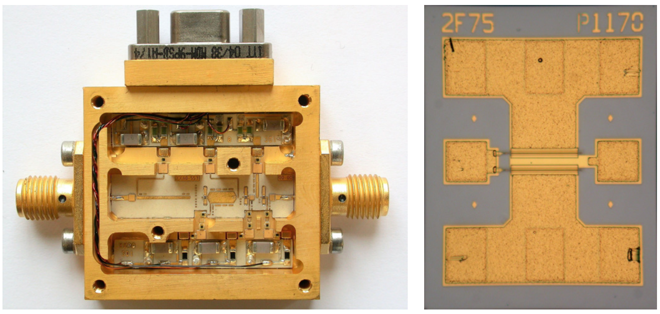

Fig. 1. On the left, ALMA LNA on which this development is based. On the right, Diramics InP transistor with two 75×0.1 µm gate fingers used in the first stage to obtain the best noise.

III. Quadrature Hybrid Coupler

The superconducting 4-12 GHz compact hybrids are fabricated on alumina and employ the three-sections planar design suggested in [5]. The central section with a Lange coupler is placed between two sections with coupled line couplers. The Lange coupler provides the highest coupling coefficient while the other two sections are loosely coupled.

The whole design features superconducting transmission lines to minimize the insertion loss, have better control of the transmission line geometry and ease the manufacturing of the devices. The hybrids are produced using thin-film microfabrication technology that combines photolithography and dry etching processes for the formation of superconducting Nb transmission lines, and galvanically plated air bridges to connect the coupler fingers in the middle section. The overall size of the miniature hybrid chip is as small as 27x9 mm and is currently limited only by the pitch required between the through and coupled ports, in order to conveniently interface with the existing LNA structures.

The performance of the hybrids has been verified on a single witness hybrid sample that was selected from the same wafer as one of the three units used for this work. The S-parameters of the witness hybrid have been measured at 4K, using a 4-port VNA connected to a cryostat, similarly to [7]. The results show excellent performance of the hybrids in terms of insertion loss, return loss, as well as amplitude and phase imbalance (see Fig. 3).

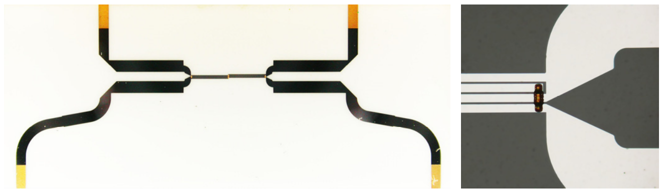

Fig. 2. On the left, photograph of the hybrid chip, 27×9 mm. On the right (in inverted colors), detail of the Lange coupler section and air bridge.

IV. Balanced Amplifier Design and Fabrication

A. Modular balanced LNA

Two identical LNAs as described in section II were connected to two quadrature hybrid modules to test the performance of a balanced configuration (see Fig. 4) and compare it with the compact version. The connectorized hybrid modules are made of CuTe and include a prior version of the chip described in section III, with slightly worse input reflection [7].

Similar modular balanced amplifiers had been tested in the past at Yebes Observatory [2], but not with superconducting lines. The validity of this approach was demonstrated before proceeding with the fabrication of the compact balanced version by including this amplifier on a complete 300 GHz receiver, where an advantage in noise terms over the pre-existing isolator solution was measured [7].

B. Compact balanced LNA

The integration of the balanced amplifier into a single module was attempted as a proof of concept to validate its potential advantages. In this first attempt no effort was put on the size reduction of the module (one of the benefits of the integration). As shown in Fig. 5, the amplifier comprises two specular versions of the individual LNA, sharing only the drain bias circuit cavity. No changes in the microstrip matching circuits were made. Both DC connectors were

[1] Diramics AG, Hinterbergstrasse 28, 6312 Steinhausen, Switzerland (http://diramics.com/).

[2] Millimeter-Wave Electronics Laboratory, Eidgenössische Technische Hochschule (ETH), Zürich

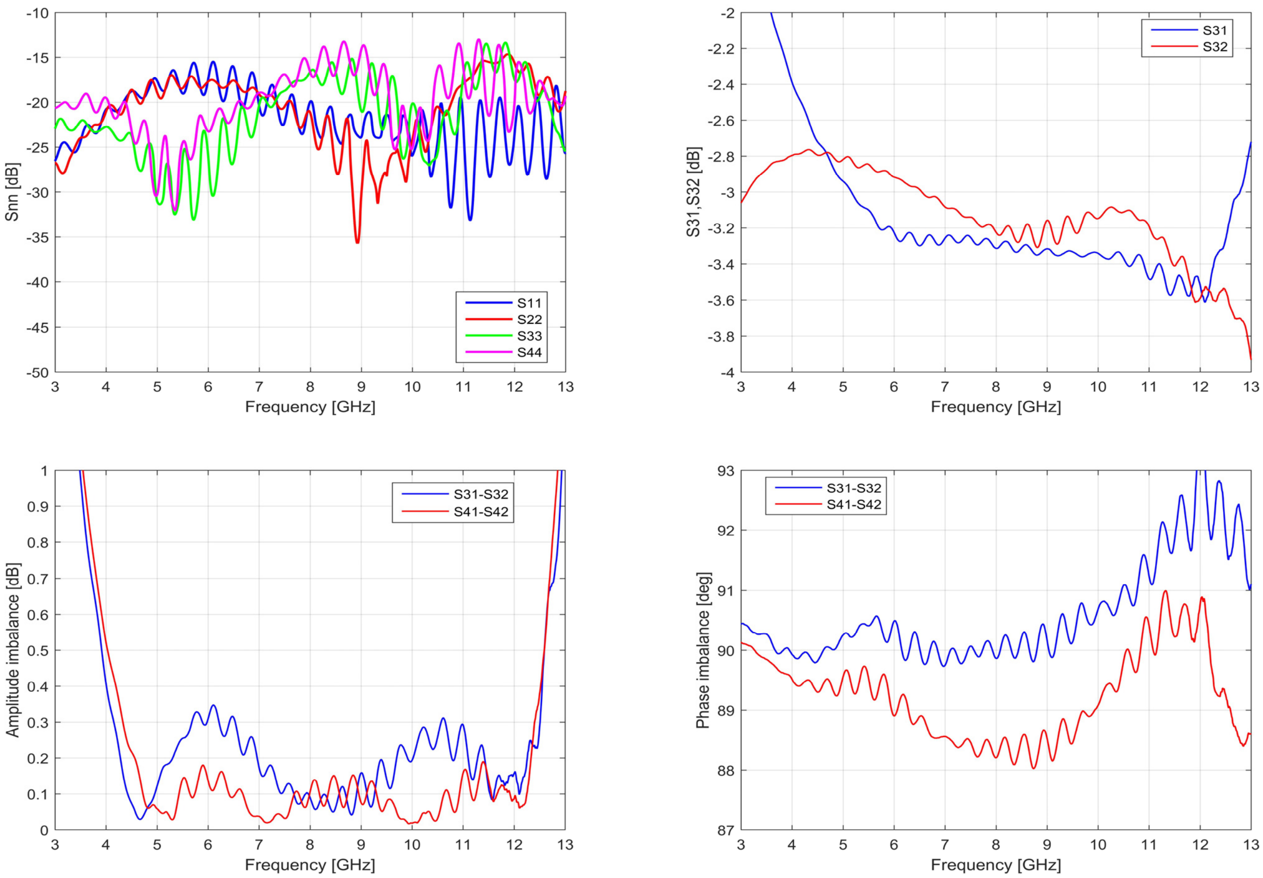

Fig. 3. Performance of the superconducting hybrid. From left to right, top to bottom, return losses, insertion losses, amplitude imbalance and phase imbalance.

preserved to simplify the design.

The interface of the microstrip line with the hybrid chip consists of a coaxial hermetic seal (glass bead) with a stress relief contact on both ends to avoid cracking of the soldering due to differential thermal contraction between pin and line.

One key advantage of this design is the possibility of performing measurements of each amplifier independently. This can be achieved before attaching the hybrid blocks to the dual amplifier chassis, by simply placing 2.9 mm coaxial connectors on the outer end of the glass beads pins. These measurements (1) allow a direct comparison of the single ended vs the balanced configurations and (2) facilitate the tuning of the individual amplifiers.

All mechanical parts (amplifier chassis, hybrid blocks and lid) were machined in CuTe at Chalmers GARD workshop and gold plated at Yebes Observatory. The overall dimensions without connectors are 53×52.4×12.5 mm.

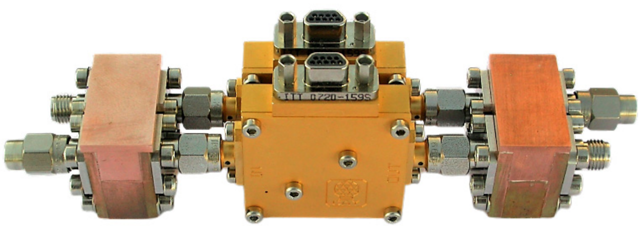

Fig. 4. Modular balanced LNA used in the first tests. It comprises two individual LNAs as in Fig. 1 and two hybrids.

V. Results

A. Measuring system

Cryogenic noise measurements were performed at Yebes Observatory. Two different setups were used to characterize the amplifiers.

The validation and tuning measurements of the LNAs included in the compact balance amplifier were done in a 15 K Dewar using the cold attenuator method. A HP N8975A noise figure meter was used in combination with an Agilent N4002A noise source, and an in-house-built 15 dB attenuator specially designed in a quartz substrate [8] for broadband cryogenic operation and accurate temperature readings. The main reason for using this setup was the advantage it gives for tuning an amplifier in terms of speed (due to the fast-switching noise diode) and the possibility of measuring cryogenic S parameters simultaneously.

The balanced amplifiers with superconducting hybrids (T_c around 9 K) were measured in a 5 K Dewar using the controlled temperature load method. In this case, the noise source is broadband very low reflection coaxial termination connected directly to the LNA input inside the cryostat. It is based on a GaAs chip featuring a 50 Ω load and an integrated

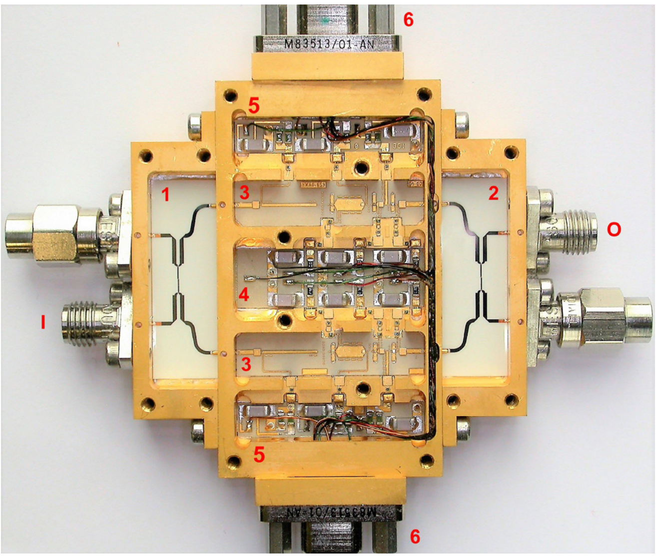

Fig. 5. Compact balanced LNA, sized 53×52.4×12.5 mm without connectors. Input (I) and output (O) are 2.9 mm coaxial connectors. 50 Ω loads are connected to the other hybrid ports. Note the input (1) and output (2) hybrid chips assembled into detachable modules, the specular RF cavities (3) as in the original LNAs of Fig. 1, the common gate bias cavity (4), the drain bias cavities (5) and DC connectors (6) of each amplifier. Hybrid blocks can be substituted by 2.9 mm connectors enabling direct measurements of the individual LNAs.

heating resistor and temperature sensor, fabricated by IAF[3] [9]. Its temperature can be controlled in closed loop using the heater and the sensor, and the temperature of the cold plate is controlled as well by an independent loop (allowing measurements at different temperatures). A photograph of the setup inside the Dewar is shown in Fig. 6.

The final measurements of the individual LNAs were also taken in this system at 5 K to provide a homogeneous comparison with the balanced LNA. Data at 15 K were also obtained, showing very good agreement with the measurements taken in the 15 K Dewar with the other method.

Cryogenic S parameter data was measured at 5 K in the same Dewar using a Keysight PNA-X N5247A and Keysight

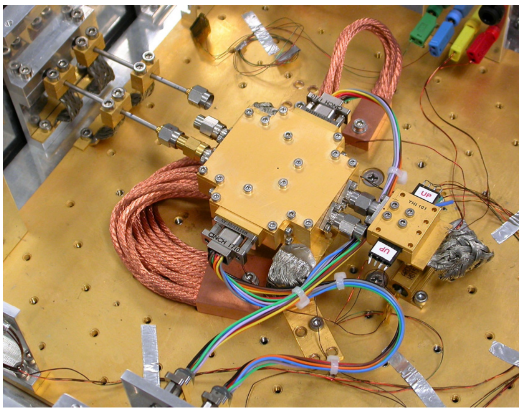

Fig. 6. Noise measurement setup in the 5 K Dewar. A cryogenic heatable load [9] is connected to the input of the compact balanced amplifier.

[3] Fraunhofer Institute for Applied Solid State Physics, Tullastrasse 72, 79108 Freiburg, Germany (https://www.iaf.fraunhofer.de/)

N4694A electronic calibration kit used in place of the DUT at ambient temperature inside the Dewar. Stainless steel access lines are supposed invariant with temperature. The loss change with temperature of the flexible cable connecting the DUT with the output line is subtracted from the S11 and S21 and its residual phase variations upon cooling are eliminated by time domain gating.

B. *Experimental results*

Comparisons between a modular balanced amplifier and an isolator in this band had been presented previously [4], [7], showing an advantage in noise in favor of the balanced option. In this section we will focus only on the measurements of the balanced amplifiers.

Figure 7 shows the noise and gain curves of the compact balanced amplifier, its individual LNAs (measured before the assembly of the hybrid blocks) and the modular amplifier. The balanced amplifier noise is almost bounded between the noise of its amplifiers. It is remarkable that the average noise in the band is 4.4 K, only 0.3 K more than both LNAs averaged, which demonstrates the importance of the low losses of the superconducting hybrid lines and the close integration of hybrid and LNA. The noise degradation in the compact balanced amplifier noise with respect to a single-ended is

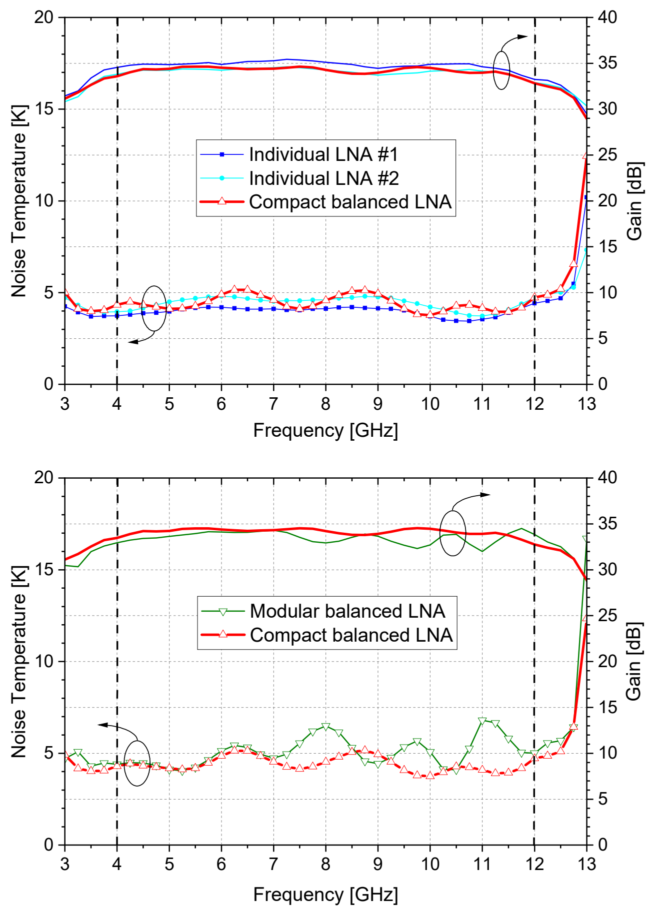

Fig. 7. Noise and gain curves of the compact balanced LNA compared to its individual LNAs (up) and the modular balanced LNA (down), measured at 5 K.

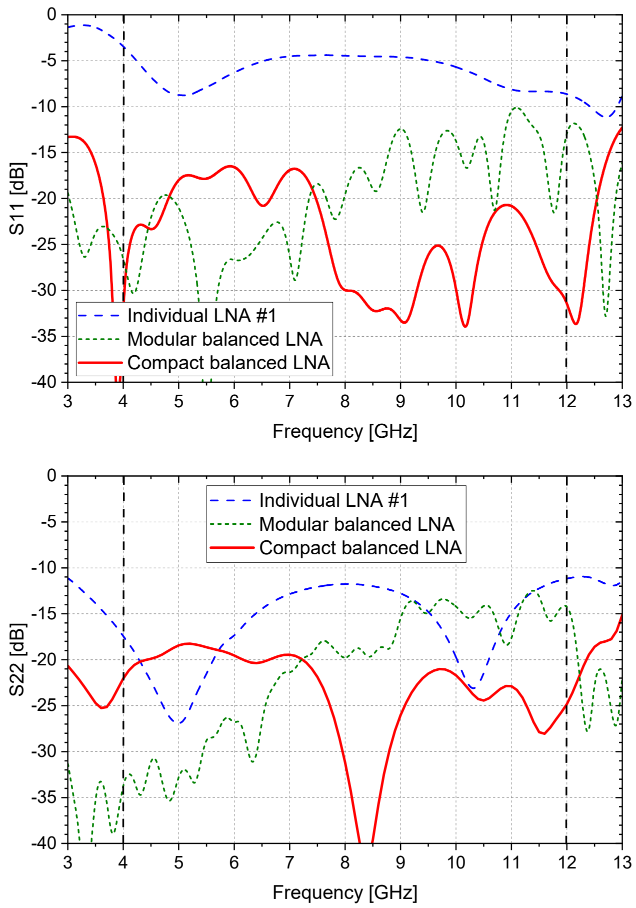

Fig. 8. Input (up) and output (down) reflection of the compact balanced LNA (solid red) compared to one individual LNA (dashed blue) and the modular balanced LNA (short dashed green), measured at 5 K

higher probably due to the losses and mismatches in the connectors, and to the slightly more reflective hybrids used. This is even clearer in the noise (and gain) ripple, produced by stationary noise waves in the balanced amplifier. While the compact balanced amplifier presents less than 1 K peak to peak, the modular balanced ripple is 2.7 K. Note that the amplifier is being measured in 50 Ω setup in which the single-ended amplifiers noise is quite flat. In a real non-matched environment, the amplifiers will be exposed to the mixer reactive load and the system noise and gain ripple (due in this case to the stationary waves between the mixer and the LNA) will be much higher with the non-balanced amplifier.

The input and output return losses of the three configurations are shown in Figure 8. As expected, the balanced configuration improves the single amplifier reflection, especially at the input which is much more difficult to match for a wide band low noise amplifier. The variation is more than 10 dB between the single-ended and the compact balanced versions. The improvement of the compact balanced amplifier with respect to the modular version is more evident in the higher end of the band.

The results collected in this section were obtained at 5 K ambient temperature and with the same bias for the amplifiers. They are summarized in Table I. The bias used optimizes the performance (noise, gain flatness and output reflection) of a single-ended amplifier, while keeping a discrete power dissipation (7.5 mW). It was replicated in the balanced amplifiers to ensure that the results were perfectly comparable. The power dissipation of a balanced amplifier is then roughly twice that of one individual LNA, and this is not a minor issue for certain applications with very restricted cooling power. However, a significant reduction of this power consumption is possible in a balanced amplifier by retuning the bias of the last amplifying stages: the output return losses are not affected as they are dominated by the hybrid reflection. Preliminary tests showed that a 25% reduction is easily attainable (11.5 mW overall) with only a minor impact in the gain flatness (less than 1 dB increase).

TABLE I
PERFORMANCE OF THE DIFFERENT LNA CONFIGURATIONS TESTED

@ 5 K, 4-12 GHz	**Single ended** [a]	**Modular balanced** [b]	**Compact balanced**
Average Noise (pp) (K)	4.1 (1.0)	5.1 (2.7)	4.4 (1.4)
Average Gain (pp) (K)	34.4 (2.0)	33.5 (2.5)	34.1 (1.7)
IRL max. (dB)	-3.5	-10	-16.4
ORL max. (dB)	-11.2	-12.3	-18.3
Power dissipation [c] (mw)	7.5	15	15

[a] Values presented are the average of both LNAs used in the compact balanced.
[b] Individual amplifiers are not the same as in the compact balanced, but of identical design and transistor batches. Hybrids differ slightly in its design.
[c] Balanced amplifier measured with the same bias as single amplifiers. Further power dissipation reduction is possible.

At the time of this writing, the compact balanced LNA has already been measured in a 300 GHz receiver at GARD with excellent results which will be made available soon.

VI. CONCLUSION

A cryogenic compact balanced low noise amplifier has been designed, fabricated and critically compared with its single-ended amplifiers and with a similar non-integrated balanced LNA. This unit benefits from excellent 3 dB quadrature hybrid coupler and LNAs designs, as well as Diramics InP 0.1×150 µm transistors. The superconducting lines negligible losses and the tight integration are responsible for the very low noise increment of just 0.3 K (measured at 5 K) with respect to the individual LNAs and for the reduced noise ripple of less than 1.5 K pp in the 4-12 GHz band. As expected from a balanced configuration, the input return loss is drastically improved and lies well below 15 dB. Such performance makes this type of amplifiers excellent candidates for the IF of wide band mm-wave receivers and demonstrates its potential for wider bands, for which other alternatives are not possible (like cryogenic isolators) or degrade significantly the performance (like single-ended amplifiers).

Additional improvements of the compact balanced amplifier design are under study, such as the simplification of the bias circuitry, the integration of a mixer bias T, a further reduction in size or the extension of the bandwidth to higher frequencies.

REFERENCES

[1] J. Carpenter, D. Iono, L. Testi, N. Whyborn, A. Wootten, N. Evans, "The ALMA Development Road Map," ALMA Observatory, Jun. 18, 2018. [Online]. Available: https://www.almaobservatory.org/wp-content/uploads/2018/07/20180712-alma-development-roadmap.pdf

[2] P. Grimes, R. Blundell, S. Paine, C.-Y. E. Tong, L. Zeng, "Next generation receivers for the submillimeter array," *Proc. SPIE 9914, Millimeter, Submillimeter, and Far-Infrared Detectors and Instrumentation for Astronomy VIII*, 991424, Jul. 19, 2016.

[3] I. López-Fernández, J. D. Gallego Puyol, C. D. González and A. B. Cancio, "Development of Cryogenic IF Low-Noise 4-12 GHz Amplifiers for ALMA Radio Astronomy Receivers," *2006 IEEE MTT-S Int. Microwave Symp. Dig.*, San Francisco, CA, 2006, pp. 1907-1910.

[4] I. Malo-Gómez, J. D. Gallego-Puyol, C. Diez-Gonzalez, I. López-Fernández and C. Briso-Rodriguez, "Cryogenic Hybrid Coupler for Ultra-Low-Noise Radio Astronomy Balanced Amplifiers," *IEEE Trans. Microwave Theory Tech.*, vol. 57, no. 12, pp. 3239-3245, Dec. 2009.

[5] H. Rashid, D. Meledin, V. Desmaris, A. Pavolotsky, V. Belitsky, "Superconducting 4–8 GHz Hybrid Assembly for 2SB Cryogenic THz Receivers", *IEEE Transactions on Terahertz science and Technology*, 4 (2) pp. 193-200. 2014.

[6] J. Schleeh et al., "Cryogenic LNAs for SKA band 2 to 5," *2017 IEEE MTT-S International Microwave Symposium (IMS)*, Honololu, HI, 2017, pp. 164-167.

[7] D. Meledin, V. Desmaris, E. Sundin, H. Rashid, A. Pavolotsky, J. D. Gallego, I. López-Fernández, C. Diez, V. Belitsky, "A 1 mm SIS Receiver Utilizing Different IF Configurations," presented at the *30th International Symposium on Space Terahertz Technolgy*, Gothemburg, Sweden, Apr. 15-17, 2019.

[8] J. L. Cano, N. Wadefalk and J. D. Gallego-Puyol, "Ultra-Wideband Chip Attenuator for Precise Noise Measurements at Cryogenic Temperatures," *IEEE Trans. Microwave Theory Tech.*, vol. 58, no. 9, pp. 2504-2510, Sept. 2010.

[9] D. Bruch, R. I. Amils, J. D. Gallego, M. Seelmann-Eggebert, B. Aja, F. Schafer, C. Diez, A. Leuther, M. Schlechtweg, O. Ambacher, I. Kallfass, "A Noise Source Module for In-Situ Noise Figure Measurements From DC to 50 GHz at Cryogenic Temperatures," *IEEE Microwave and Wireless Components Letters*, vol. 22, no. 12, pp. 657-659, Dec. 2012.

[10] V. Belitsky, *et al.*, "Facility Heterodyne Receiver for the Atacama Pathfinder Experiment Telescope", *IRMMW-THz 2007* Cardiff, UK, 2007.