Development of Cryogenic IF Low-Noise 4-12 GHz Amplifiers for ALMA Radio Astronomy Receivers

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***Abstract* — We describe the design and results of a wide band C-X cryogenic IF amplifier developed for band 9 (602-720 GHz) of ALMA radio telescopes. A cryogenic 4-12 GHz isolator will be used at the input to improve matching. Several units have been fabricated and its results are presented. The amplifiers utilize HRL InP transistors to achieve a noise temperature of 5.3 K (0.08 dB NF) on average. Gain fluctuations are critical for the project. Values of Allan variance lower than 4.1 10^{-9} (0.1 s ≤ T ≤ 10 s) have been obtained.**

***Index Terms* — Amplifier noise, broadband amplifier, cryogenic electronics, IF amplifiers, MODFET amplifiers, radio astronomy, submillimeter wave receivers.**

I. Introduction

Radio astronomy is the most demanding application in terms of sensitivity at sub-millimeter frequencies. In coherent receivers, the signal is mixed by Semiconductor-Isolator-Semiconductor (SIS) mixers and Hot Electron Bolometers (HEB) which usually have a significant conversion loss. Cryogenic low-noise amplifiers, generally used in the front-end of radio astronomy receivers for frequencies up to 100 GHz, have then a crucial role also as IF amplifiers for the sub-millimeter band.

Astronomers require for every new generation of instruments not only lower noise, but wider instantaneous bandwidths to be able to detect more distant molecular lines with higher Doppler redshifts, and increase the sensitivity in continuum observations. The Atacama Large Millimeter Array (ALMA) is the most important radio astronomy project currently under construction by European and North American Institutes. It is an interferometer of 50 antennas 12 m each located 5000 m high in the Chilean desert, covering the 30-950 GHz band with several dual polarization receivers [1]. The IF bandwidth needed per polarization is 8 GHz.

Europe is in charge of two of the four channels initially developed: band 7 (275-370 GHz, IRAM leads) and band 9 (602-720 GHz, NOVA leads). IRAM's approach is a 4 GHz dual-sideband (2SB) receiver. NOVA has chosen an 8 GHz double-sideband (DSB) design. IF amplifiers for all European bands are being developed by our group. Two designs have been produced: 4-12 GHz for NOVA, described here, and 4-8 GHz for IRAM (double number of amplifiers).

The amplifier is conceived as a stand-alone sub-unit and can be tested in a standard 50-Ohm coaxial environment. This is very convenient due to the modular design of the European receivers to facilitate the integration of the contributions of different groups. To overcome the problem of the mismatch between the mixer and the amplifier, a cryogenic isolator must be used at the output of the mixer. PAMTECH has demonstrated cryogenic isolators for this band. The insertion losses of this element must be minimized to reduce its noise contribution. Other approaches include integrating the amplifier close to the mixer [2].

The project requirements of minimum noise temperature, high gain and low power dissipation (less than 3 mW per stage to reduce the thermal load) motivated a design with three stages of InP HEMT devices. This technology has established its superiority over GaAs for low-noise low-power cryogenic applications [3]. However, with the increase of bandwidth and the reduction of noise temperature, another factor limiting the sensitivity began to play an important role: the gain fluctuation. InP devices have greater fluctuations than GaAs, especially at cryogenic temperatures.

II. Design and Fabrication

The amplifier is a microstrip hybrid design. A large number of units must be fabricated, so reliability, repetitivity and easy manufacturability play a central role in the design and are important enough to make concessions in the electrical performance. The specifications are listed in Table I. Previous experience in the qualification of spatial projects [4] was applied to this design.

A. Devices selection and characterization

InP technology was selected for the HEMT transistors, after our experience with other amplifiers at C and X bands. Most applications of this material took advantage of its high cut-off frequency to produce higher frequency amplifiers. Its use in intermediate frequency (IF) stages brings up stability problems that require a careful design technique.

The transistors S parameters including bond wires were measured at cryogenic temperatures (13 K) for several bias points using a special microstrip test-fixture which allows for a cryogenic two-tier TRL calibration up to 40 GHz. The values of the intrinsic elements of the equivalent circuit are fitted from the S parameters data, while the parasitics are obtained from DC and coldFET. The noise characteristics of the transistors were modeled following Pospieszalski [5], with a gate temperature equal to ambient and a drain temperature extracted from cryogenic noise measurements of the device in the first stage of a wide band two-stage test amplifier with an adjustable element, which can easily match transistors of similar gate widths.

The devices used were provided by HRL in lattice-matched, 0.1 µm technology, and are described in detail in [6]. Even though it is a relatively old design it still has a good performance. They were chosen due to its proven reliability, reproducibility and availability for the project. The gate width selected was 150 µm (easier to match in this frequency range).

All other elements used in the design were carefully selected based on previous experience at cryogenic temperatures. Capacitors and resistors were modeled taking into account the variation with temperature of dielectric constants and film resistivities. The microstrip matching circuits are implemented in DUROID 6002 10 mils laminate (ε_r=2.94).

B. Electrical and mechanical design

The microwave equivalent circuit of the amplifier was simulated with MMICAD. The design comprises three stages. Each transistor was independently stabilized in the band by a resistive loading in drain and an inductive feedback in source, which also contribute to equalize the gain and bring together the minimum noise and input conjugate impedances. In the design of the matching circuits the goal was to obtain a good compromise between low noise, high flat gain and low output return loss.

Several tuning elements in the form of patches to modify some line impedances or lengths were added to the design and used in the final adjustments of the amplifier. Especially useful is the matching of the minimum noise impedance of the transistors varying the inductance of the gate bonding wires.

The amplifiers were completely manufactured in our laboratories and workshops. A picture of one of them is illustrated in Fig. 1. The housing is machined in aluminum and gold plated to provide mechanical protection and allow gold wire bonding of the transistor source pads. SMA connectors with removable contact (the sliding pin withstand easily thermal stress) are used in the signal input and output. Microwave substrates and most components are epoxied to the chassis. Two additional cavities at both sides of the microwave channel allocate the bias PCBs for gate and drain respectively. These circuits include several RC sections to filter the microwave signal and help stabilizing the transistors and also voltage and charge dividers to grant ESD protection.

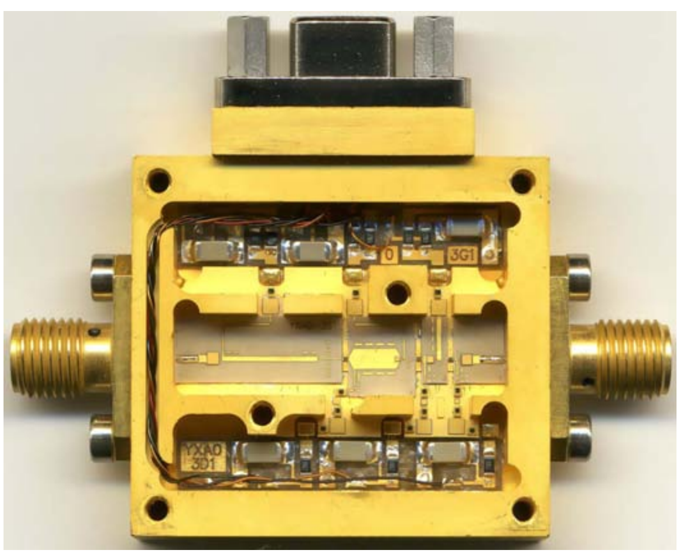

Fig. 1. Photograph of an ALMA Band 9 4-12 GHz amplifier with the cover removed. The box dimensions are 32×29×9 mm (with cover, excluding connectors).

III. MEASUREMENTS AND RESULTS

We present in Table I a summary of the performance of the first 4 pre-production amplifiers delivered to ESO compared to the specifications of the project. Follows a description of the measurement techniques and a more detailed presentation and analysis of the results.

TABLE I
SUMMARY OF PERFORMANCE AND SPECIFICATIONS

Parameters measured @ 4-12 GHz, T=14 K, P_D < 9 mW		Average 4 LNAs	Best of 4 LNAs	Specs.
Noise [K]	Average	5.3	5.0	<6
	Maximum	6.1	5.8	8
Gain [dB]	Average	33.4	34.0	30<G<35
	Excursion	1.87	1.75	<3
IRL [dB]	Maximum	-3.4	-3.7	-3
ORL [dB]	Maximum	-15.2	-15.5	-10
Stability	Minimum [1]	1.5	1.7	1
Fluctuations	Maximum [2]	$4.6\cdot10^{-9}$	$4.1\cdot10^{-9}$	$2\cdot10^{-8}$
P1dB [dB] [3]	Minimum	—	-12.7	-20

[1] Rollet factor K measured at all frequencies
[2] Allan variance $\sigma^2(2,T,T)$ measured for 0.1 s ≤ T ≤ 10 s
[3] Only amplifier YXA 1004 tested for compression

A. Noise temperature

Noise temperature was measured, as all other parameters, in a 14 K dewar. An improvement of around 1 K in average noise can be expected by further cooling the amplifier to the nominal operating temperature of 4 K, and has been measured [7]. The cold attenuator method was used, with an estimated absolute accuracy of ±1.4 K (3σ), and repeatability one order of magnitude better [8]. This method allows good accuracy even for amplifiers with high input reflection and can be implemented with commercially available equipment (Agilent N8975A).

Fig. 2 presents the results of the first 4 amplifiers delivered. The average noise in the band is around 5.3 K. The minimum noise temperature of the amplifier is less than a degree above the minimum attainable of the transistors (represented by the dashed line in the graph). This noise is less than an order of

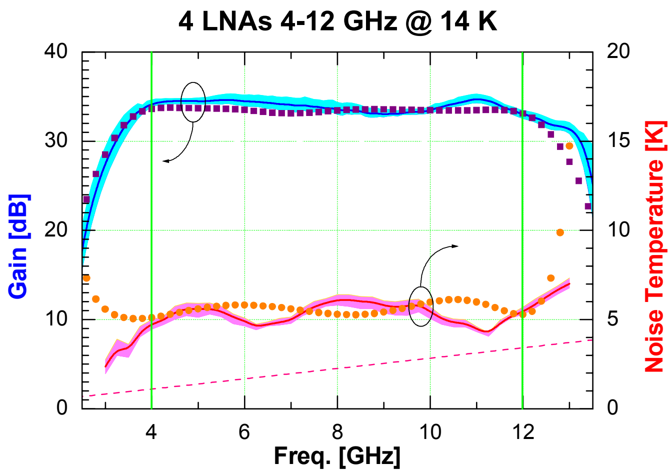

Fig. 2. Modeled and measured gain and noise of 4 LNAs (YXA 1001-4). The colored bands are defined by worst and best values for all the amplifiers. The solid line is the average of the series. The dots correspond to the noise model and the squares to the gain model. The dashed line represents the minimum noise temperature of the device. There are some "bad points" in the noise data below 4 GHz. This was caused by the poor performance of the room temperature 4-12 GHz isolator at the input of the NFM in this range.

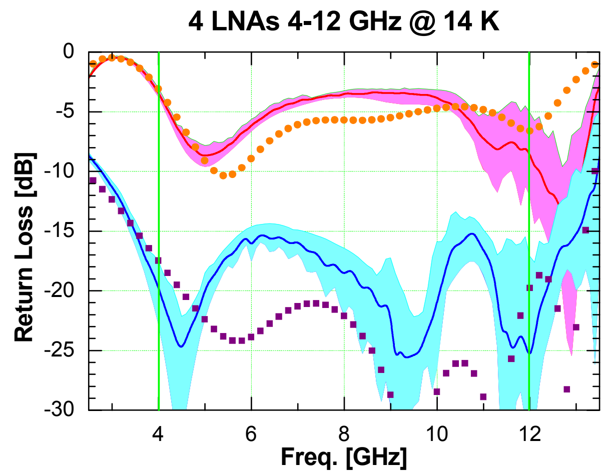

Fig. 3. Modeled and measured input and output return losses of 4 LNAs (YXA 1001-4) in the same fashion as the noise and gain plot of Fig. 2.

magnitude above the quantum limit. Note the consistency of the data for all amplifiers, shown in the small width of the colored band containing all the curves.

B. S parameters

S parameters were measured with a vector network analyzer and referred to the input and output of the amplifier.

The Rollet stability factor was calculated from the S parameters. All amplifiers are unconditionally stable at all frequencies.

Average gain is around 33.4 dB (see Fig. 2). Gain excursion in the band has been reduced by tuning below 2 dB. Note again the low dispersion between units in gain results.

Output return loss is less than -14.5 dB in the whole band for all units. Input return loss is not a design parameter, due to the presence of the cryogenic isolator at the input, but must be kept below -3 dB to limit the gain ripple of the system in the band due to the non ideal output reflection of the isolator. Return losses are represented in Fig. 3. It is apparent that the curves dispersion is higher than in Fig. 2, due to the different tuning of the units to improve gain flatness.

The 1 dB compression point is well above -20 dBm. The dynamic range is more than needed even for solar observation.

C. Gain fluctuations

In ALMA the value of the fluctuations for the cryogenic amplifier, specified in terms of Allan variance of the normalized gain, is set to $\sigma^2(2,T,T) < 2\cdot10^{-8}$ (for $0.1\text{ s} \leq T \leq 10$ s). The specification in terms of Allan variance is very convenient for the astronomers, but for the engineers is better to use the Spectrum of Normalized Gain Fluctuations (SNGF). Some features of periodic nature like temperature oscillations of the refrigerator or power supply ripple are then easily identified and can be distinguished from the intrinsic fluctuations due to the devices.

The SNGF of the amplifier has been measured for CW 8 GHz signal using two different techniques: a) Vector Network Analyzer and b) quadratic detector, preamplifier and FFT Spectrum Analyzer. Fig. 4 presents the results obtained and the measurement system noise floor with each technique. Note the spectral line at 1 Hz caused by the cycle of the mechanical cooler and the interference of the mains supply. The results show a very good fit with 1/f noise in the frequency range accessible to the measurements. From these data the Allan

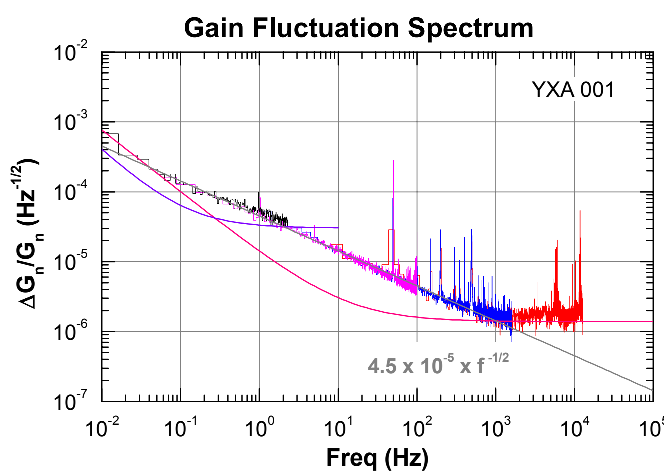

Fig. 4. Spectrum of normalized gain fluctuations for a prototype 4-12 GHz amplifier. The noise floor of the a) and b) measurement systems is represented by the solid curves. Experimental data is shown for different sampling times.

variance can be easily calculated.

The intrinsic gain fluctuations of the devices are known to depend on its physical structure and on several extrinsic factors, namely bias point, temperature, illumination. With the nominal bias used in this amplifier the result obtained is lower than our previous experience [4], and similar to the best values found by others [9], [10]. Four more amplifiers were measured with similar fluctuation values, well within the initial specs.

D. Isolator measurements

The increment in noise temperature ΔT_c produced by an isolator connected to the input of an amplifier is given by

$$\Delta T_c = \left(\frac{1}{G_{iso}} - 1 \right) \cdot \left(T_{amb} + T_{amp} \right), \; G_{iso} = \frac{|S_{21}|^2}{1 - |S_{22}|^2}, \quad (1)$$

where T_{amb} is the physical temperature of the isolator, T_{amp} is the equivalent noise temperature of the amplifier and G_{iso} is the available gain of the isolator.

Fig. 5 shows the results of one of the prototypes developed by PAMTECH. The noise contribution of this isolator at 4 K ambient temperature to one of the amplifiers of Fig. 2 is, according to (1), between 1 K in the center of the band and 2.6 K near the band edges.

IV. Conclusions

We have demonstrated 4-12 GHz cryogenic amplifiers with an average in the band at 14 K ambient of 5.3 K of noise temperature, 34 dB of flat (±0.9 dB) gain and -15 dB of return loss, unconditionally stable and dissipating less than 9 mW. Noise temperatures are very close to the minimum attainable with the InP HRL devices used. An improvement around 1 K is expected at 4 K ambient.

The amplifier was designed for the ALMA band 9 SIS mixers, but it is a robust stand-alone unit that can be used in combination with a commercially available isolator in any new generation sub-millimeter receiver with this IF band. The noise degradation of 1-2.6 K due to the isolator it is expected to improve with the next generation of PAMTECH isolators. A total of 18 units will be fabricated in the pre-production phase of the project, of which the results of the first 4 have been presented, showing a good consistency.

The gain fluctuation measured in the prototype amplifier is almost a factor of two better than the value obtained in a similar project with different devices [4].

Acknowledgement

The authors would like to thank the technical assistance of Rafael García, Gonzalo Martínez and Daniel Geijo in amplifier and substrate fabrication. This work has benefited from research funding from the European Community's sixth Framework Programme under RadioNet R113CT 2003 5058187 and from the Spanish Administration grant (Ministerio de Ciencia y Tecnología) AYA2003-07584.

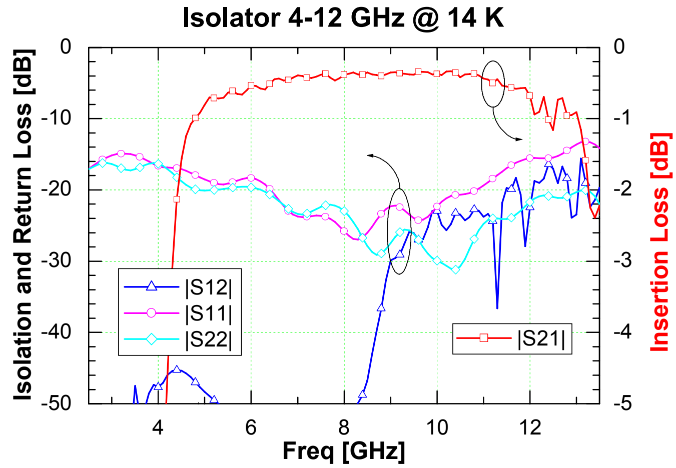

Fig. 5. S parameters of a PAMTECH isolator prototype model 55387. The manufacturer is only able to measure the isolators at 77 K. Cooling down to 14 K produces a frequency shift in the characteristics that still needs further calibration.

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