ALMA MEMO 421

GaAs-BASED CRYOGENIC AMPLIFIER FOR ALMA 2SB MIXER

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Abstract

As part of Onsala Space Observatory instrumentation activities, a 4-8 GHz cryogenic low-noise amplifier was developed. This 2-stage LNA demonstrates 26 dB gain with noise temperature of 5.0 K using commercial GaAs transistors MGFC4419G from Mitsubishi. The total power consumption is of about 12 mW while with a total power consumption tuned down to 4 mW, the gain drops to 24 dB and the noise is of 6.0 K. This performance is in a very good agreement with simulations and believed to be among the best-reported using GaAs transistors. The amplifier design was carried using Agilent ADS, HFSS and Momentum CAD software. This amplifier will be used as a cold IF amplifier for mm and sub-mm wave receivers with SIS and HEB mixer, primarily for APEX Project as well in our development of ALMA band 7 sideband separation mixer providing two independent IF channels (USB and LSB) of 4-8 GHz, therefore fulfilling the 8 GHz bandwidth requirements for ALMA. In this paper we present details on the amplifier design, performances (modelled and measured) and gain-stability comparison between GaAs and InP transistor based amplifiers.

Introduction

Millimetre and sub-millimetre wave receivers for high resolution spectroscopy in radio astronomy are usually of a super heterodyne type; the receiver employs frequency down-conversion based on superconducting SIS or HEB mixer operating at 4 K or lower ambient temperature; the sky signal transfers to an intermediate frequency (IF) signal of a few GHz and is amplified by a cryogenic low-noise amplifier. Nowadays, radio telescope receivers employ IF amplifiers with typically 1 GHz bandwidth centred either at 1.5 GHz or 4 GHz. But with the increasing interest for sub-mm observations, larger bandwidths are required for broader spectral line and continuum observations of extragalactic sources. ALMA specifications call for a total IF bandwidth of 8 GHz per polarization channel, therefore DSB mixer requires a 4-12 GHz IF band amplifier while for sideband separation (2SB) mixer, two 4-8 GHz IF amplifiers are needed to cover the 8 GHz bandwidth.

The LNA described here is planned to be used as cold IF amplifier for Onsala APEX Project development (APEX antenna to be installed in Chilean Atacama desert in the fall of 2003). The amplifier will be used for Onsala ALMA band 7 (345 GHz band) sideband separation mixer tests in the lab. This LNA will also be used as a front end

of C band and X band receivers on 20 m and 25 m antennas at Onsala Observatory. The present paper is part of a more extended publication where a 3.4-4.6 GHz LNA is also described [1].

Amplifier Design

Design was carried out using Agilent ADS [2]. To achieve desirable accuracy of the modelling, the transistors were simulated using their S parameters at cryogenic temperature [3], and special attention was paid to develop adequate models of the passive components (resistors and capacitors). For example, the capacitor models include the series resistance and take into account series resonance as well as the first parallel resonance. The model consists of a series R-L-C circuitry with parallel R-C branch and the values were chosen to fit the manufacturer S-parameters data. In order to improve the stability and the input match, the bond wires, connecting the transistor source to the ground, and the resistors in the drain bias paths, provide the inductive feedback. The bonding wire model was developed using 3D EM simulation Agilent HFSS [4].

The most critical part in the design is the amplifier input stage where a 50 Ohm input line (from SMA connector) has to be transformed into a complex impedance varying with frequency and which should be as close as possible to the optimum noise match of the given transistors. The input stage uses a low impedance line, followed by a high impedance line with a tuning stub, to slightly increase the bandwidth, which is a part of the transistor gate bias line (Figure 1). This input stage was built as a separate test unit and precise measurement with a TRL calibration helped us to adjust performance of the entire amplifier for the optimum by changing the bypass capacitor location (±1 mm). The inter-stage and the output-stage were optimised for maximum gain, gain flatness and for the output match. The amplifier uses soft substrate, Duroid 6002, having excellent dielectric constant thermal stability and the coefficient of thermal expansion matched to that of copper. We use ATC chip capacitors of 100A series that show low series resistance and behave well at cryogenic temperature and surface mount series RC31 resistors. All the passive components are soldered using alloy 80In15Pb5Ag; for the substrate we used alloy 70In30Pb and the transistors are soldered using pure Indium. Bias lines are separated from the RF lines by a sidewall to avoid oscillations at low frequencies and the box resonance.

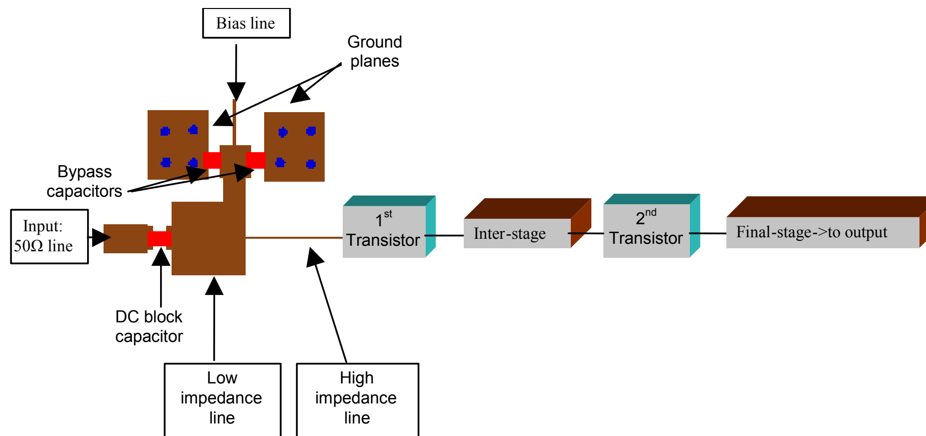

Figure 1. The amplifier block diagram and the input circuitry schematic.

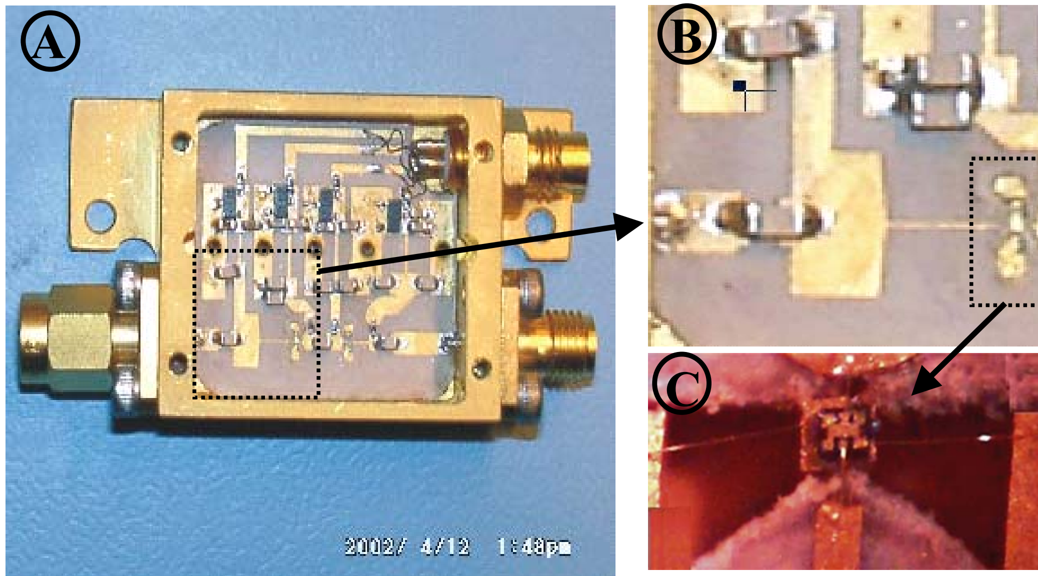

Figure 2. ***A:*** *Photograph of LNA 4-8 GHz with outer dimensions 50*26 mm.* ***B:*** *Magnified view of the input circuitry consisting of a low impedance wide line and a high impedance narrow line. Position of the capacitors provides a mean of tuning the noise performance.* ***C:*** *Magnified view of a GaAs HEMT chip transistor Mitsubishi MGFC4419G. Long bond wires from the source pads to ground provide inductive feedback and improves stability.*

We chose the option of having a cold isolator at the input of the amplifier: this facilitates the design of the amplifier input circuitry; its input reflection coefficient is required to be only less than -5 dB. However, the insertion loss of the isolator adds of about 10% to the noise when connected to the amplifier input.

Results

Two methods were used in our laboratory to measure the noise performance of the amplifiers: the variable load temperature (VLT) method and the cold attenuator (CA) method, both employing the Y-factor technique via connecting matched loads at different temperatures (T_{hot}, T_{cold}) at the input of the device. The accuracy of amplifier noise temperature measurement was carefully investigated and estimated for both methods [5] for the given laboratory measurement setups and is of ±0.4 K for the VLT method and ±0.8 K for the CA method. Though being less accurate, the CA method is less time consuming than the VLT method, it is much more convenient for sweep measurements when optimising bias voltages. Results with both methods are very consistent, and the below results all were taken with the CA method.

The LNA gives 26 dB (±1.5 dB) gain and noise temperature of 5 K with a total power consumption of 15 mW (figure 5). With a low power consumption of 4 mW, results are 24 dB gain and 6 K noise temperature. Replacing the first stage transistor with Chalmers InP HEMT [6] gives 26 dB gain with a 4.0 K noise temperature and the total power consumption is 4 mW.

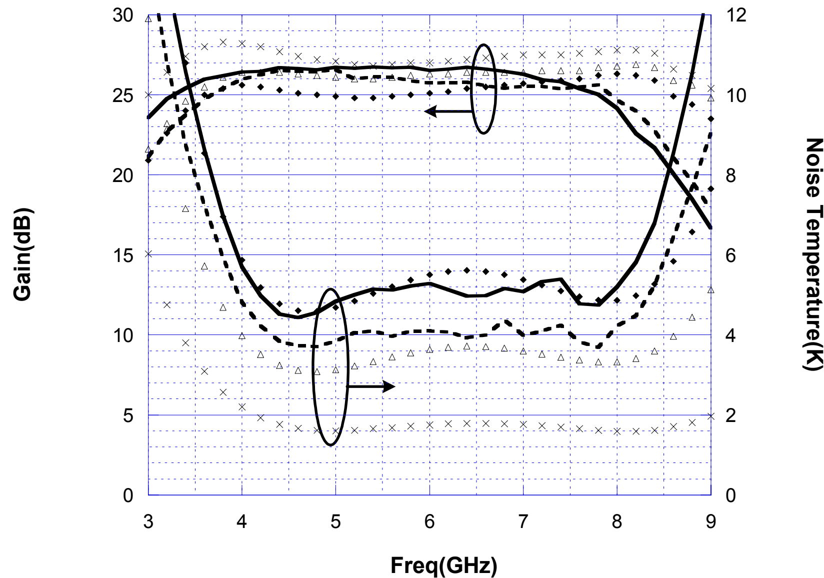

Figure 5. Simulations and measurements results for 4-8 GHz *LNA: The bottom curves are noise temperature plots and the upper curves are gain plots. Continuous line is for measurement of GaAs MGFC4419G for both stages, dashed line is for measurement of the LNA by replacing the first stage transistor by Chalmers InP HEMT. The diamond marked line shows simulation results for GaAs-based LNA, the line with triangles is simulation results for Chalmers InP-based LNA, and the plot with crosses is simulation results for TRW InP-based LNA*

The amplifier input match S11 is less than –5 dB, as expected, and the output match S22 is better than –12 dB. At room temperature the GaAs-based LNAs have 24 dB gain and 35-40 K noise temperature.
The agreement between the simulation and the measurement is good, which is in part due to very accurate models for the transistors extracted by I. Angelov [6]. The simulations also show that with InP transistors from TRW, the noise temperature should drop below 2.0 K.

Gain Stability Studies

A comparison between GaAs and InP HEMT [5] transistors was carried out in order to estimate their relative gain stability. Two methods were used: the first method uses the Allan Variance [7-9] while the other method employs the power spectra of the noise (with FFT) and measures its normalized gain fluctuation value at 1 Hz [10].

A possible source of the gain instability is the variation of the ambient temperature; the low noise amplifiers under test were mounted on the cold plate of a 2-stage close cycle refrigerator providing the temperature of 12 K. The cold plate temperature was monitored continuously, and the temperature fluctuation due to the compressor cycle (1 Hz) was of about 5 mK; however, this is a lower limit of the measured temperature variations with fast fluctuations apparently filtered out because of the response time of temperature sensors; it was found that this has negligible effect on the gain of the LNA. Moreover no 1 Hz line was seen in the power spectra taken showing that our set-up is not sensitive to the compressor cycle, as opposed to the results in [9, 10].

The measurement procedure is described in [10] and employs a stable CW signal of 4.25 GHz, injected into the input of the amplifier with the output power monitored with a Boonton power detector. The power level was maintained constant to get 20 dBm at the input of the detector. The data was taken every 500 ms and we were looking at the gain instabilities in a narrow bandwidth around 4.25 GHz. To avoid influence of the setup on the measurement results we calibrated the system alone, without the amplifiers under test; the calibration shows that it is stable to at least 50 s (see figure 6), which is sufficient for our tests.
The measurement presented here were taken with a GaAs based 4-8 GHz LNA, with Vd=1.8 V and Id=5 mA for both stages, and the second InP-based 4-8 GHz LNA had an InP transistor at the first stage with Id=0.6 V and Id=3 mA and the GaAs transistor for the second stage.

Allan variance shows the relation between obtained sensitivity as a function of integration time. For ideal case when only white noise is present, Allan variance should follow a 1/T slope (radiometer formula). The different types of noise can be described by the following expression:

$$A\,\mathrm{var}(T) = c \cdot T^{\beta} \qquad (1),$$

where b = -1 is for white noise, b = 0 is for 1/f electronic noise, and b = 1 is for low frequency drifts. With this type of representation, one can easily identify the type of the noise present, and determine what is the optimum integration time to get the best sensitivity. This time limit is called Allan Time, integrating more would not give any improvement and could even degrade the signal to noise ratio.

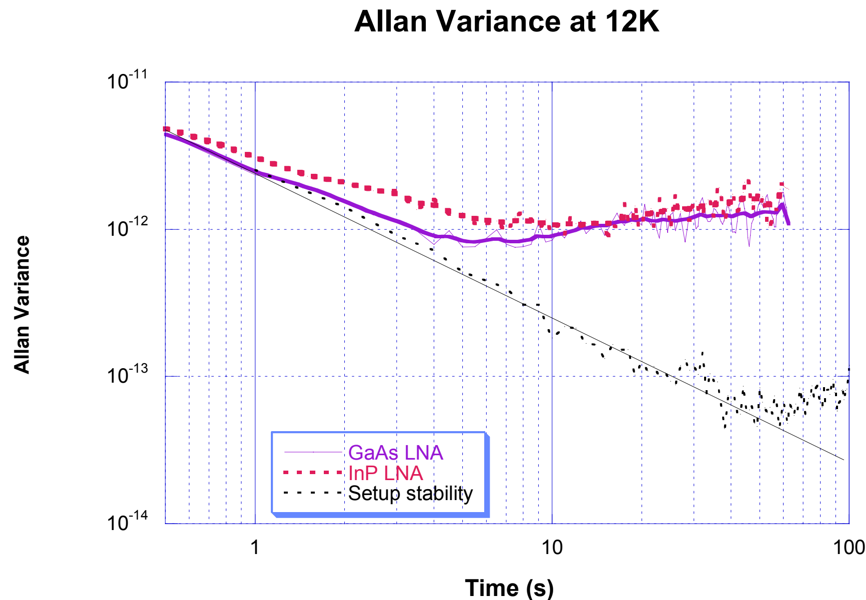

Figure 6. Solid line is for GaAs based LNA, and dashed line for InP based LNA. Already at 1s, there is a loss of integration efficiency and InP-based LNA deviates earlier than GaAs. At 7s 1/f noise become dominant for both amplifiers.

Figure 6 shows Allan variance plot; already at 1s there is a loss of integration efficiency, data points deviate from the ideal 1/T slope. This early deviation could be caused by some microphonic pickup noise on the LNA bias lines. At about 7s, 1/f

noise becomes dominant, and Allan Variance stays at a constant level, slightly increasing due to the presence of some low frequency drift.

Taking the power spectra of the noise (with FFT) gives basically the same type of information as the Allan variance and shows the power spectra of different type of noises. The expression for the power spectral density of different type of noise is the following:

$$S(f) = b \cdot \left(\frac{1}{f}\right)^{\alpha} \qquad (2),$$

for the white noise $a = 0$, for the 1/f electronic noise $a = 1$, for the low frequency drift $a = 2$.
Figure 7 shows the normalized power spectra of the same data as in Figure 6. 1/f noise is clearly visible for frequencies < 1 Hz. Then the white noise becomes dominant for frequencies above 1Hz.

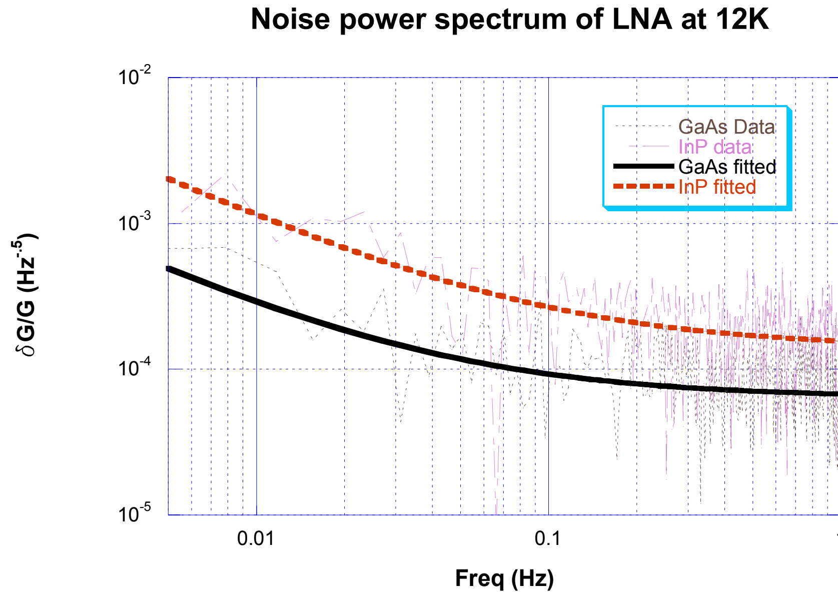

Figure 7. Normalized noise power spectrum for the same measurement as in Figure 4. Solid line is for the GaAs based LNA, dashed line is for the InP based LNA.

Here again, it is clearly seen that InP-based LNA has poorer stability than GaAs-based LNA. The values at 1 Hz are:

$$b_{GaAs} = 8 \cdot 10^{-5}\ Hz^{-0.5} \qquad\qquad b_{InP} = 15 \cdot 10^{-5}\ Hz^{-0.5}$$

It should be noted that no correction was applied to the data to subtract the measurement set-up intrinsic instability. Therefore the values above are the total instability of the LNA and the set-up itself.
Both methods give consistent results, showing that InP-based LNA are slightly worse than GaAs-based LNA for the gain stability. From Kraus [11], the gain instability degrades the sensitivity in a total power receiver as:

$$\delta T = T_{SYS} * \sqrt{\frac{1}{B*\tau} + \left(\frac{\delta G}{G}\right)^2} \quad (3),$$

where T_{sys} is the system noise temperature, B is the effective bandwidth, t - the integration time, and $\delta G/G$ the gain fluctuations of the receiver.

From this formula, it can be seen that for a large instantaneous bandwidth or large integration time, the stability of the receiver becomes an issue. If the LNA gain fluctuation is negligible compared to other gain fluctuations in the receiver like the SIS mixer conversion gain, then the LNA should have the lowest noise temperature to get the lower T_{sys} and therefore the lower δT. But if the LNA gain fluctuation is the dominant source of instability in the receiver, there is a trade-off to look for, and in some cases it could be worth using the more stable LNA, in spite of a slightly higher noise temperature.

Conclusion

A 4-8 GHz low-noise 2-stage amplifiers based on GaAs HEMT transistors was designed and tested as part of our development work at Onsala Space Observatory. The amplifier design was carried out using Agilent ADS, HFSS and Momentum CAD and special attention was paid to model the passive components and the matching circuitry correctly and use accurate cold transistor S-parameters. The measured performance at cryogenic temperature of 12 K is 26 dB gain and 5.0 K noise temperature with GaAs HEMT and 4.0 K with Chalmers InP HEMT for the first stage. The total power consumption for optimum noise performance was in the range of 12-15 mW with GaAs and of 4 mW with Chalmers InP; however the GaAs-based LNA can still be used with 4 mW total power consumption with little performance penalties of 1 K noise temperature increase and 2 dB gain drop. These results represent the state of the art for these frequency ranges with commercial GaAs transistors.

The gain fluctuation measurement of the HEMT devices shows that GaAs-based LNA are slightly better than InP-based LNA in term of gain stability. In some cases, e.g., for receivers using large detection bandwidth or integration time in a single run, and having gain fluctuations mainly due to the LNA itself, a better receiver sensitivity could be achieved using GaAs based LNA rather than InP LNA, even despite having a slightly higher noise temperature.

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