LOW NOISE CRYOGENIC IF AMPLIFIERS FOR SUPER HETERODYNE RADIOASTRONOMY RECEIVERS

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Abstract

As part of Onsala Space Observatory instrumentation activities, a 3.4-4.6 GHz and a 4-8 GHz cryogenic low-noise amplifiers were developed. These amplifiers will be used as cold IF amplifier for mm and sub-mm wave receivers with SIS and HEB mixer (Onsala 7 channel 3mm array and APEX projects). The 2-stage 3.4-4.6 GHz amplifier was fabricated in 7 copies with consistently very similar performance at 12 K ambient temperature as follows: gain 28 dB with 2.8 K noise temperature using Mitsubishi MGFC4419G GaAs transistor, and 2.2 K noise when tested with Chalmers InP transistor at the first stage. The 2-stage 4-8 GHz LNA demonstrates 25 dB gain with noise temperature of 5.0 K with GaAs transistors, 4.0 K with Chalmers InP transistor at the input stage. These performances are in a very good agreement with simulations and are believed to be among the best-reported using GaAs transistors. The amplifiers design was carried using Agilent ADS, HFSS and Momentum CAD software. The amplifier input circuitry was measured separately and optimised for the best noise performance, while special care was taken about accurate modelling of passive components, bond wires and having accurate S parameters at cryogenic temperature for the transistor. In this paper we present details on the amplifier design, performances (modelled and measured) and also 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. Next generation of IF amplifiers will have 4 GHz bandwidth or even 8 GHz.

The first LNA presented here is designed for frequency band 3.4-4.6 GHZ [1], and is to be used as cryogenic IF amplifier for 3-mm wavelength 7 channel SSB receiver to be installed at Onsala 20m telescope. The other LNA is designed for the frequency band 4-8 GHz, and will be used as cold IF amplifier for our development of ALMA band 7 receiver (345 GHZ band) and also for APEX Project (to be built in Chilean Atacama desert end of 2002, and to be included in ALMA later on). The 4-8 GHz amplifiers will also be used as a front end for Onsala C band receivers on 20 m and 25 m antennas.

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.

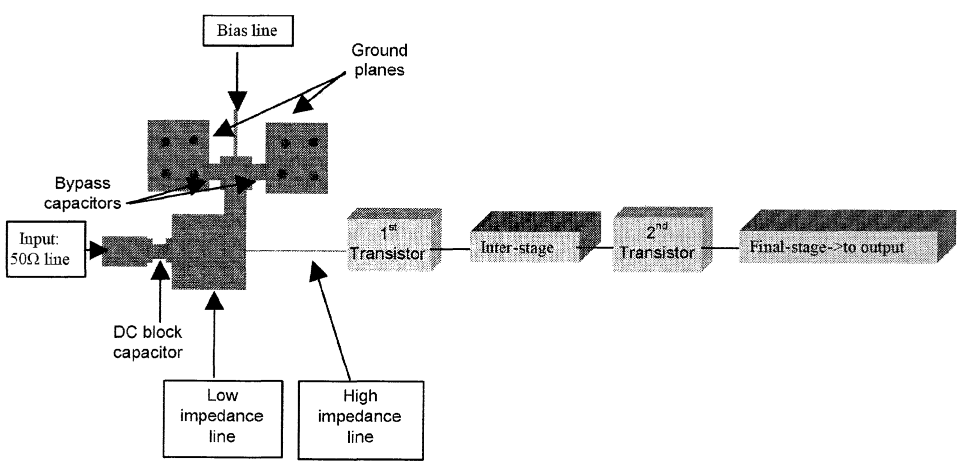

Figure 1. The amplifier block diagram and the input circuitry schematic.

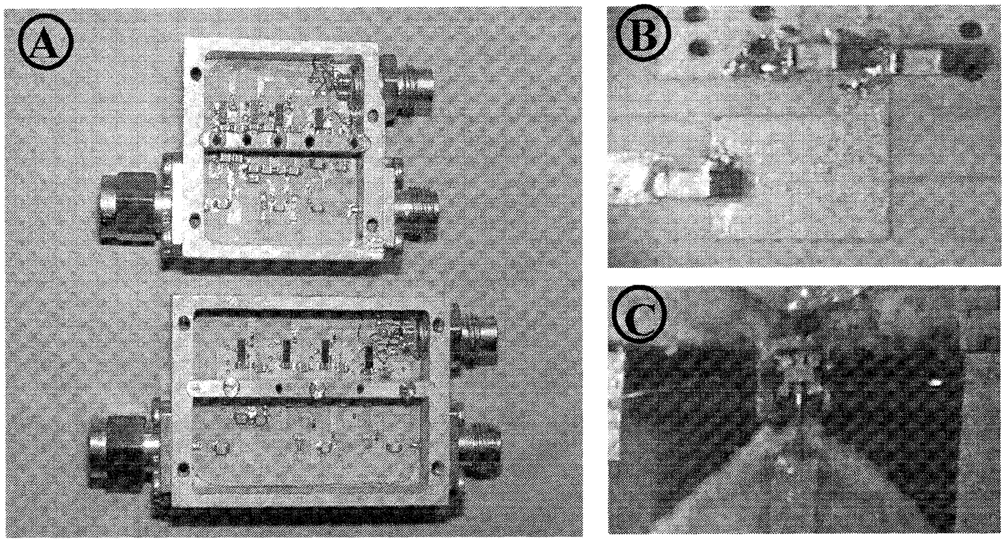

*Figure 2. **A:** Photograph of LNA 3.4-4.6 GHz (bottom one) with dimensions 65*26 mm and LNA 4-8 GHz (top one) with dimensions 50*26 mm. **B:** Magnified view of the input circuitry of LNA 3.4-4.6 GHZ. It consists of a low impedance wide line and a high impedance narrow line. Position of the capacitors 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 cooled 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. But 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 amplifier under test (DUT), and to measure the output powers corresponding to the different load temperatures. As the DUT is assumed to be linear, the two measurement points are sufficient. The noise temperature T_e is then estimated as:

$$T_e = \frac{T_{hot} - Y \cdot T_{cold}}{Y - 1} \quad \text{, where} \quad Y = \frac{P_{hot}}{P_{cold}} \text{ measured at the output of DUT.}$$

VLT method (Figure 3) is a direct Y-factor measurement where we used a 50-Ohm load with a heater installed inside the cryostat on the cold plate and connected to the input of the amplifier through a short piece of a stainless steel coaxial cable providing thermal insulation. When the heater is OFF, the load is almost at the ambient cryogenic temperature 12 K (measured by a precision thermometer), whereas when the heater is ON the temperature up to 40 K can be reached.

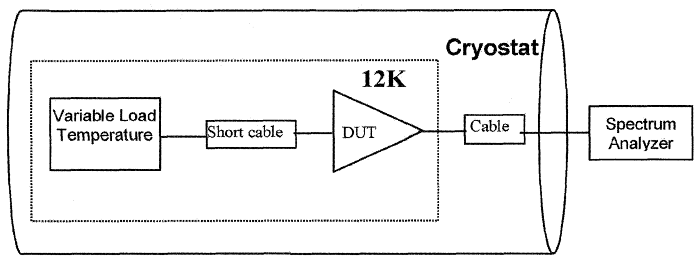

Figure 3. Variable Load Temperature Method

The CA method employs a cold attenuator and an external noise source, the noise diode HP346B with 15 dB ENR, operating together with the noise figure meter HP8970B. The noise signal from the diode is applied to the input of the amplifier under test via the precision 23 dB attenuator (Figure 4). By biasing the noise diode, the signal at the amplifier input can be changed from 50 K (9000 K from the noise source attenuated by the 23 dB cold attenuator) to 12 K when the noise source is OFF and the amplifier sees mainly the thermal noise from the attenuator at 12 K ambient temperature. The use of cold attenuator reduces the effect of the cable connecting the noise diode operating at room temperature to the attenuator at 12 K; the loss in the cable and its equivalent noise temperature can be only roughly estimated. The cold attenuator help also to improve the match of the noise source with the DUT, the noise diode impedance varies significantly between ON and OFF.

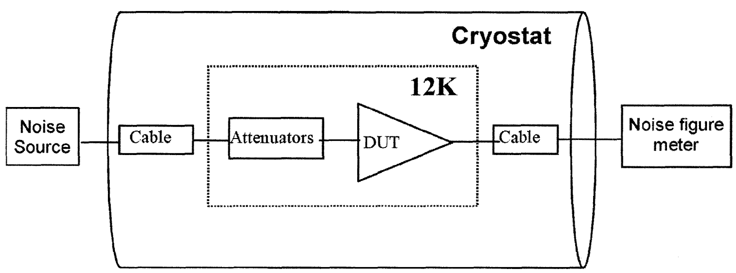

Figure 4. Cold Attenuator Method

The accuracy of amplifier noise temperature measurement was carefully investigated and estimated for both methods [2] 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. Therefore, results presented below were all taken with the CA method at cryogenic temperature of 12 K and moreover the few results with the VLT method are very consistent with the CA measurements.

3.4-4.6 GHz GaAs-based LNA (figure 5) gives 28 dB gain and the noise temperature of 2.8 K with total power consumption of 12 mW (optimised for the best noise performance). With a low power consumption of 4 mW, the amplifier has 26 dB gain and the noise temperature of 3.3 K, which is still very good. Replacing the first stage transistor with Chalmers InP HEMT [3] gives 28 dB gain with lower noise temperature of 2.2 K and total power consumption of 4 mW.

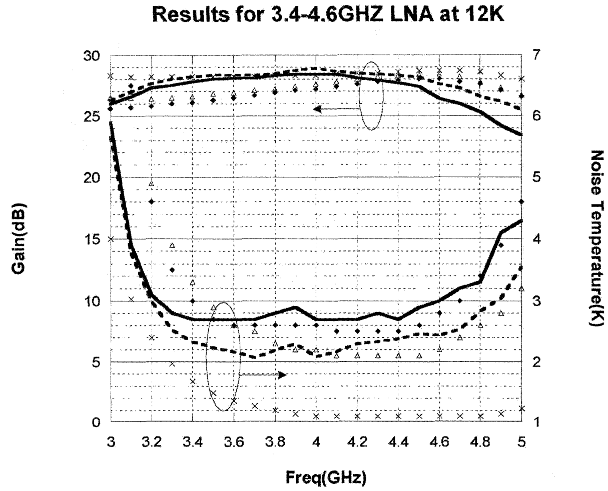

Figure 5. Simulations and measurement results for 3.4-4.6 GHz LNA: The bottom curves are noise temperature plots and the upper curves are gain plots. Continuous line is for measurement of GaAs MGFC4419G for both stages, dashed line is for measurement of the LNA by replacing the first stage transistor 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.

For the 4-8 GHz, (figure 6) GaAs based LNA gives 26 dB (±1.5 dB) gain and noise temperature of 5 K with a total power consumption of 15 mW. With a low power consumption of 4 mW, results are 23 dB gain and 6 K noise temperature. Replacing the first stage transistor with Chalmers InP HEMT gives 26 dB gain with a 4.0 K noise temperature and the total power consumption is 4 mW.

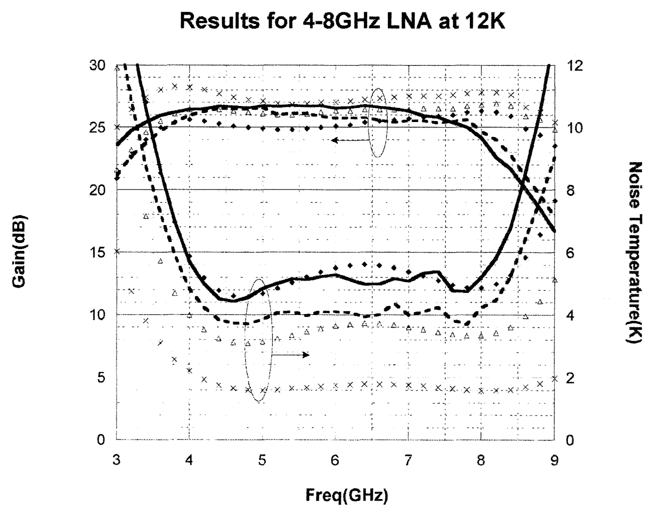

Figure 6. Simulations and measurements results for.4-8 GHz LNA: The bottom curves are noise temperature plots and the upper curves are gain plots. Continuous line is for measurement of GaAs MGFC4419G for both stages, dashed line is for measurement of the LNA by replacing the first stage transistor by 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 for the both LNAs. At the cryogenic temperature (12 K), the measurement of the 3.4-4.6 GHz LNA together with a cooled isolator gives a noise temperature of about 3K, with slightly narrower bandwidth, which is still quite acceptable and within the specifications. The isolator shows almost a perfect match to 50 Ω for the frequency range 3.4-4.6 GHz and somewhat worse match outside this band but still much better to what could be achieved without the isolator. At room temperature the GaAs-based LNAs have 26 dB gain and 35 K noise temperature for the 3.4-4.6 GHz band and 24 dB gain and 35-40 K noise temperature for the 4-8 GHz band respectively.
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 [5]. The simulations also show that with InP transistors from TRW, the noise temperature should drop to 1.0 K for the 3.4-4.6 GHz LNA and below 2.0 K for the 4-8 GHz LNA.

Gain Stability Measurements

A comparison between GaAs and InP HEMT transistors was carried out in order to estimate their relative gain stability. Two methods were used: the first method uses the Allan Variance [6-8] while the other method employs the power spectra of the noise (with FFT) and measures its normalized gain fluctuation value at 1 Hz [9].

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 [8, 9]. The measurement procedure is described in [9] 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 4.25GHz. 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 7), which is sufficient for our tests.
The measurement presented here were taken with 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 the 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.

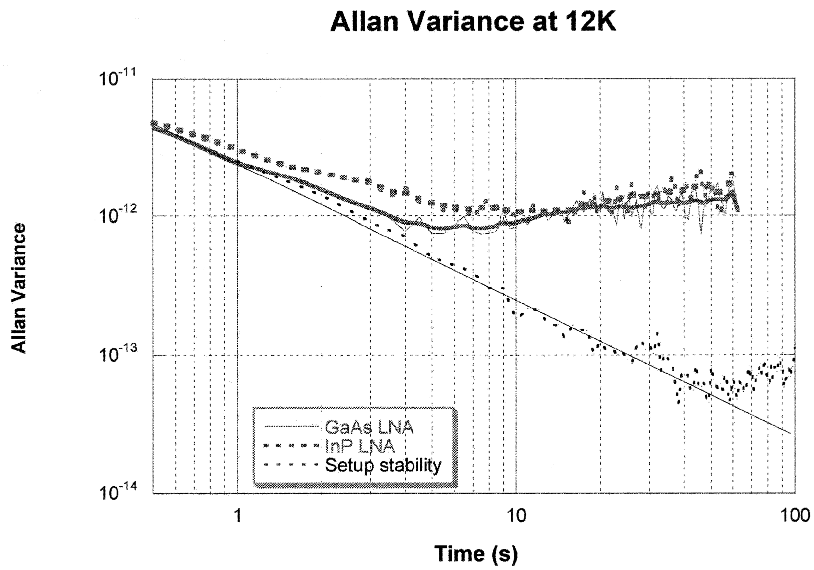

Figure 7. Solid line is for GaAs based LNA, and dashed line for InP based LNA. Already at 1s, there is a loss of integration efficiency and InP-based LNA deviates earlier than GaAs. At 7s 1/f noise become dominant for both amplifiers.

Figure 7 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 8 shows the normalized power spectra of the same data as in Figure 7. 1/f noise is clearly visible for frequencies < 1 Hz. Then the white noise becomes dominant for frequencies above 1Hz.

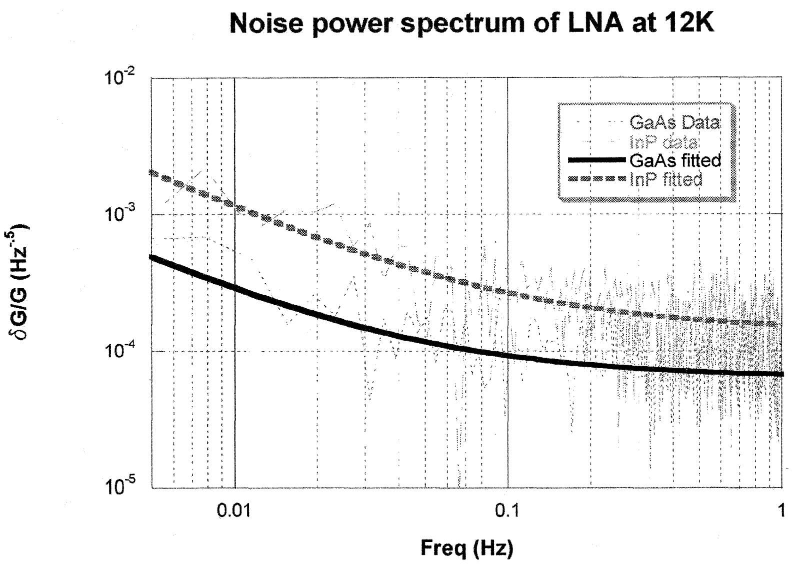

Figure 8. Normalized noise power spectrum for the same measurement as in Figure 4. Solid line is for the GaAs based LNA, dashed line is for the InP based LNA.

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 [10], the gain instability degrades the sensitivity in a total power receiver as:

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

where T_{sys} is the system noise temperature, B is the effective bandwidth, t - the integration time, and dG/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

3.4-4.6 GHz and 4-8 GHz low-noise 2-stage amplifiers based on GaAs HEMT transistors were 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 for the 3.4-4.6 GHz amplifier is 28 dB gain and 2.2 K noise temperature with Chalmers InP HEMT, and 2.8 K with MGFC4419G GaAs HEMT. For the 4-8 GHz amplifier, the performance is 25 dB gain and 4.0 K noise temperature with Chalmers InP HEMT and 5.0 K with the GaAs HEMT. These results represent the state of the art for these frequency ranges with the commercial GaAs transistors. The power consumption for optimum noise performance was in the range of 12-15 mW with GaAs and of the order of 4 mW with Chalmers InP; however the GaAs transistors can still be used with 4 mW power consumption with little performance penalties of 20% noise temperature increase and 2 dB gain drop.

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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