Low Noise and Low Power Consumption Cryogenic Amplifiers for Onsala and Apex Telescopes

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Abstract — **As part of Onsala Space Observatory instrumentation activities, several low noise, low power consumption cryogenic amplifiers were developed for frequencies between 2 and 9 GHz based on GaAs HEMT MGFC4419G from Mitsubishi. Two narrow-band amplifiers were designed, one for 3.4-4.6 GHz with 2.7 K noise temperature and 30 dB gain, the other for 8.0-9.0 GHz with 5 K noise temperature and 26 dB gain, at 12 K ambient temperature. A broadband amplifier for 4-8 GHz demonstrates 5 K noise temperature and a gain of 26 dB with 2-stages, and 34 dB with 3-stages. Lastly, a 2-4 GHz amplifier is under current development. These amplifiers are currently used at the Onsala 20 m and 25 m telescopes, Sweden, both as front-end amplifiers and as IF amplifiers for mm-wave receivers and will also be used in the new APEX sub-millimetre telescope in Atacama Desert, Chile.**

I. Introduction

Radio astronomy is probably the scientific field where the most sensitive receivers are needed to detect extremely faint sources from very distant locations. Radio astronomy receivers have always used state of the art technology, from parametric amplifiers, maser amplifiers in the 70s, to high electron mobility transistor (HEMT) [1] based amplifiers nowadays. Cryogenic operation allows decreasing drastically the amplifier noise temperature (typically an order of magnitude).

Cryogenic low noise amplifiers (LNA) are used as front-end amplifiers for frequencies up to 100 GHz [2]. For higher frequencies, the lowest receiver noise temperatures are achieved by first down-converting the signal with a superconductor-insulator-superconductor (SIS) or hot-electron-bolometer (HEB) superconducting mixers operating at 4 K ambient temperature [3]. The sky signal transfers to an intermediate frequency (IF) signal of a few GHz and is amplified by a cryogenic low-noise amplifier. The first generation of mm and submm receivers used an IF of at most 1 GHz bandwidth, centered typically 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. The next generation of receivers will have an IF of 4 GHz or even higher.

We present several cryogenic low noise amplifiers covering the bands 2 to 9 GHz, using GaAs commercial Mitsubishi MGFC4419G p-HEMT, with state of the art performance at those frequencies [4].

II. LNA Design

The amplifiers were designed with the help of Agilent Advanced Design System (ADS) and its electromagnetic solver Momentum. One of the major challenges in a successful design is to model accurately the transistors. We used very precise transistor model and S parameters and noise parameters calculated at cryogenic temperature [5]-[6] 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. In order to improve stability and input match, inductive feedback was employed using bond wires connecting the transistor source to the ground. The bond wire model was developed using 3D EM simulation Agilent High Frequency Structure Simulator.

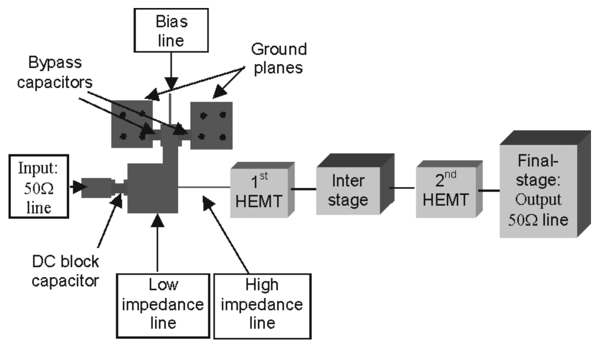

Fig. 1. The amplifier block diagram and the input circuitry schematic for a 2-stage design.

In order to achieve the lowest possible noise temperature, the most critical part in the design is the amplifier input circuitry. The 50 Ohm input line (from SMA connector) has to be transformed into a complex impedance varying with frequency that should be as close as possible to the optimum noise match of the transistors. The input circuitry uses a low impedance line, followed by a high impedance line with a tuning stub, which is part of the transistor gate bias line (Fig. 1). The input stage was built as a separate test unit and precise measurement with TRL calibration (Fig. 2) helped to adjust the performance of the entire amplifier by changing the bypass capacitor location (±1 mm). The inter-stage and the output-circuits were optimized for maximum gain, gain flatness, and output match.

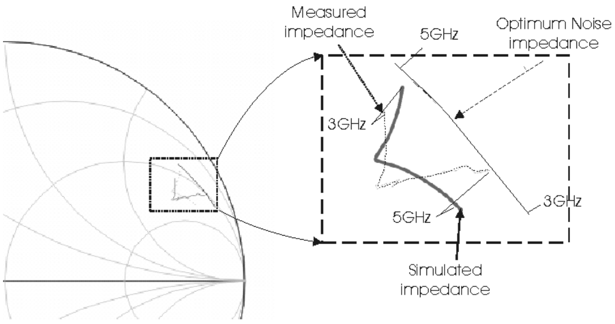

Fig. 2. Simulated and measured output impedance of the input circuitry for the 3.4-4.6 GHz LNA on the Smith Chart. Agreement is very good and quite close to the optimum noise impedance of the HEMT.

III. LNA ASSEMBLING

The amplifiers use 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. Fig. 3 shows some of the assembled amplifiers and Fig. 4 shows details of one amplifier.

Fig. 3. Photograph of the different LNAs: in the lower left is a 2-stage 3.4-4.6 GHz LNA, in the lower right is a 2-stage 4-8 GHz LNA, in the upper right is a 3-stage 4-8 GHz LNA, and in the upper left is a 8-9 GHz LNA.

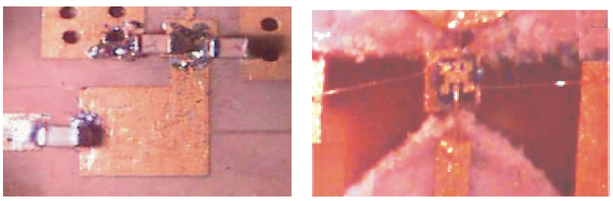

Fig. 4. Left: Magnified view of the input circuitry of a 3.4-4.6 GHZ LNA. The position of the capacitors along the tuning stub can be adjusted for tuning the noise performance. Right: Magnified view of a GaAs HEMT MGFC4419G. The bond wires from the source pads to the ground provide inductive feedback and improve stability.

IV. LNA CHARACTERISTICS

Accurate noise measurements at cryogenic temperatures are not easily achievable. We used two different techniques, known as the variable temperature load and the cold attenuator methods described in [7]. The first method gives the most accurate results (accuracy estimated to be about ± 0.5 K) but requires longer time for the measurements whereas the second method provides fast results but is more inaccurate (± 1.0 K). Comparison of the two methods gave very consistent results. Therefore all the presented results were taken with the cold attenuator method.

Furthermore measurement of a reference amplifier having 5.0 K noise temperature measured in our setup, gave in other laboratories 4.5 K (Caltech), and 4.0 K (Chalmers Microwave Electronics Laboratory).

A. 3.4-4.6 GHz LNA

When measured at a cryogenic temperature of 12 K, the 3.4-4.6 GHz GaAs-based LNA gives 28 dB gain and a noise temperature of 2.8 K with a total power consumption of 12 mW (optimized for the best noise performance). With power consumption reduced down to 4 mW, the amplifier has 26 dB gain and noise temperature of 3.3 K, which is still very good. 10 pieces of this type of LNA were built and the plots in Fig. 4 depict the performances of 4 of these amplifiers

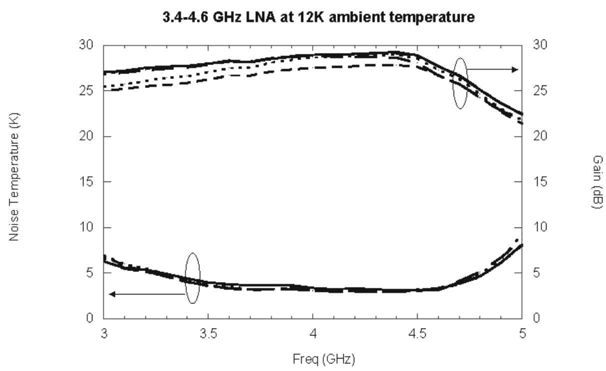

Fig. 5. Performance of series of 4 LNA, 3.4-4.6 GHz

Measurements were done with an isolator at the input of the amplifiers, adding 0.3 to 0.5 K to the noise temperature. The performance of all the amplifiers is very consistent. The gain curves differ slightly because of different bond wire lengths from the source pads to the ground. Although these amplifiers were optimized for cryogenic applications, they work very well at room temperature too. At 293 K, noise temperature is between 30-35 K (0.5 dB noise figure) and gain is 27 dB.

B. 4-8 GHz LNA

The broadband 2-stage 4-8 GHz LNA when measured at a cryogenic temperature of 12 K, gives 26 dB gain and a noise temperature of 5 K with a total power consumption of 12 mW (optimized for the best noise performance).

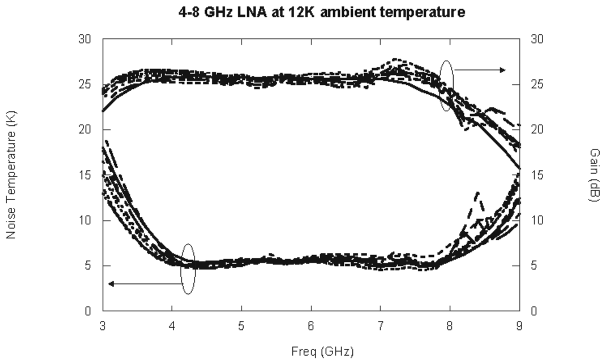

Fig. 6. Performance of series of 10 2-stage LNA, 4-8 GHz

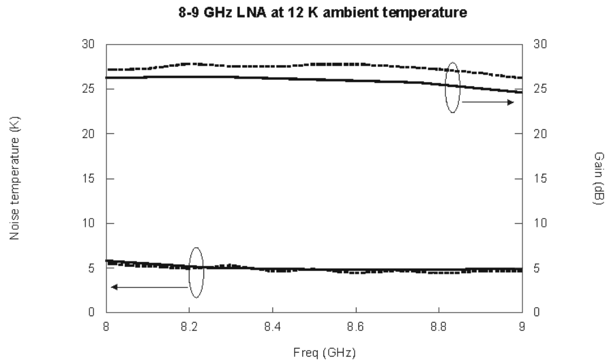

Fig. 8. Performance of 2-LNA for 8-9 GHz

With the power consumption minimized to 4 mW, the amplifier has 24 dB gain and the noise temperature degrades only to 6 K. 12 pieces of this LNA were built and performances are plotted in Fig. 6.

A 3-stage version of a 4-8 GHz LNA was developed based on the previous 2-stage version. When measured at a cryogenic temperature of 12 K, it gives 33-36 dB gain and a noise temperature of 5 K with a total power consumption of 12 mW (optimized for the best noise performance). With the power consumption minimized to 4 mW, the amplifier has 30-33 dB gain and the noise temperature increases to 6 K.

Fig. 7 compares the 2-stage and 3-stage versions. Noise temperature curves are very similar as they use almost identical input circuitries.

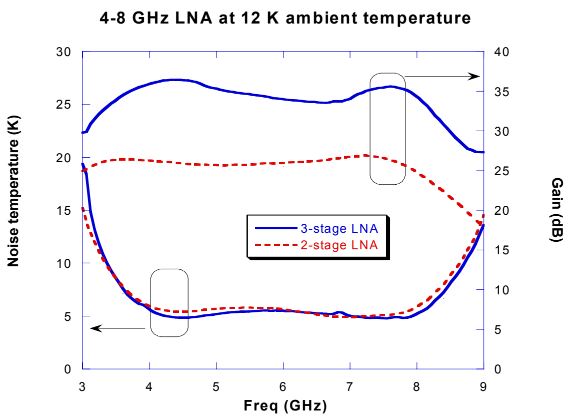

Fig. 7. Comparison between 2-stage and 3-stage LNA 4-8 GHz.

C. 8-9 GHz LNA

The 8-9 GHz LNA is a slightly modified version of the 4-8 GHz LNA with a different input circuitry. It produces 27 dB gain with a noise temperature of 5 K and the total power consumption is of 12 mW (optimized for the best noise performance). Two pieces of this LNA were built and performances are plotted in Fig. 8. At room temperature, the measured noise temperature is of 45 K and gain is of 22-25 dB.

D. 2-4 GHz LNA

A 2-4 GHz LNA is currently under development. Expected results from simulations are 26 dB of gain with a noise temperature of 4-5 K. Also input and output reflection coefficients are optimized to be lower than –14 dB over the band as there are no available cryogenic broadband isolators from 2-4 GHz with good enough performance. Fig. 9 shows the results for the noise temperature and gain and Fig. 10 shows the input and output match.

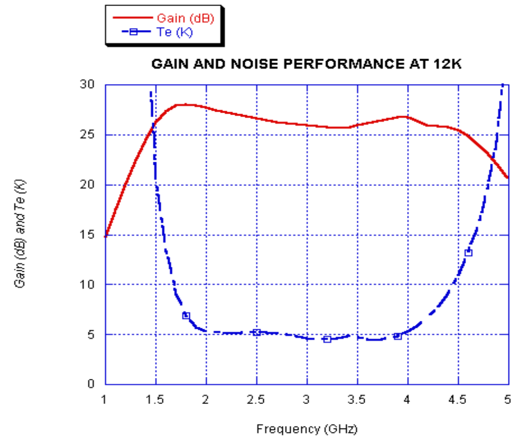

Fig. 9. Simulated gain and noise temperature at 12 K for the 2-4 GHz LNA at 12 K ambient temperature.

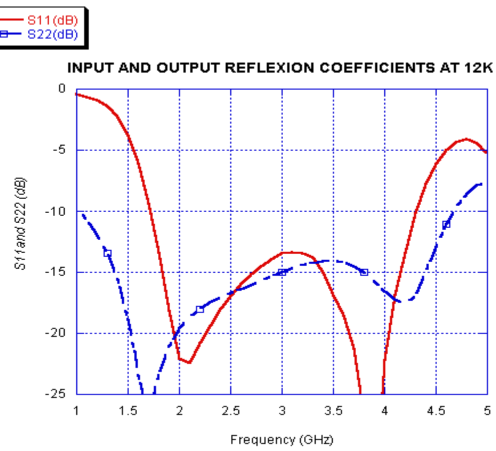

Fig. 10. Simulated input and output reflection coefficients for 2-4 GHz LNA.

IV. LNA APPLICATIONS

All the amplifiers presented in the previous sections are or will be used in radio-astronomy receivers. The 3.4-4.6 GHz LNA is used as cold IF amplifiers in a 7-channel 85-115 GHz SIS receiver to be installed at the Onsala Space observatory 20 m telescope (Fig. 11). The 4-8 GHz LNA will also be used as an IF amplifier for mm and sub-mm receivers under construction for APEX project (12 m telescope currently under completion on Chilean Atacama desert). The 4-8 GHz LNA is also employed as a frontend for dual polarization C-band receiver at Onsala Observatory 20 m and 25 m antennas. The 8-9 GHz LNA will be used for X-band receiver at Onsala 20 m and 25 m. Finally the 2-4 GHz will be used as an IF amplifier for a balanced 1.3 THz HEB receiver also on the APEX telescope.

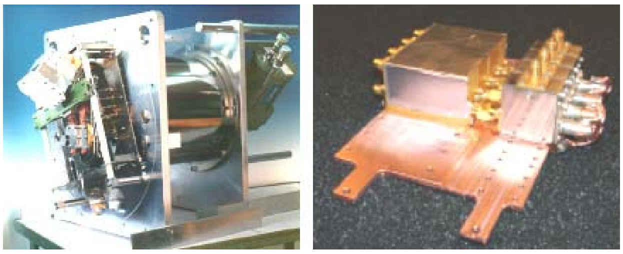

Fig. 11. Left picture: the 7-channel 100 GHz SIS receiver. Right picture: 4 of the 7 assembled isolators and 3.4-4.6 GHz IF LNAs that are mounted on the 4K cold plate of the closed-cycle cryostat.

VI. CONCLUSION

Several low noise amplifiers were designed and built in hybrid MIC technology. The transistors are commercial GaAs p-HEMTs from Mitsubishi, and the special care was taken in designing the input circuitry to optimize noise performance over the desired bands. The results achieved were a noise temperature between 0.5 K/GHz and 1 K/GHz and a gain per stage between 12 to 14 dB for 3.4-4.6 GHz, 4-8 GHz and 8-9 GHz LNAs when measured at 12 K ambient temperature with the power consumption of about 12 mW. The latter can be reduced down to 4 mW with marginal penalties in the amplifiers performance.

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