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A Low Noise 3.4-4.6 GHz Amplifier

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Abstract

A 3.4-4.6 GHz low-noise amplifier was designed and the prototype was tested at room ambient temperature and at 12 K as part of our work on 3-mm Radio Camera Project for Onsala Space Observatory. The measured amplifier gain and the *lowest* noise temperature are 26 dB and 35 K (± 5 K accuracy) at room temperature (293K) and 28 dB and 2.8 K (± 0.4 K) at 12 K ambient temperature. Commercial GaAs HEMT transistors, Mitsubishi MGF4419G, were used in this 2-stage amplifier. We present a description of the design, results of the measurements and its comparison with modelling. We also present results and error analysis for different methods of noise temperature measurement, i.e., the variable temperature load and the cold attenuator methods.

Introduction

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 mixer operating at 4 K 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. For Radio Camera Project (7-channel receiver for 3 mm wavelength) at Onsala Space Observatory, we developed this IF low-noise amplifier for 3.4-4.6 GHz to be operating at 4K. The amplifier measured noise temperature is as low as 2.8K (±0.4K) when cooled to 12K, representing the state of the art for this frequency range. But when it comes to measure such a low noise temperature, great care has to be taken in order to measure cable losses, attenuators, connectors, calibration of instruments and sensors [1]. Two methods of noise measurement, the variable temperature load (direct Y-factor measurement) and the cold attenuator, have been used and compared and the overall accuracy of the measurement estimated for both methods [2, 3].

Amplifier Design

Design was carried out using ADS from Agilent [4]. To achieve desirable accuracy of the modelling, the transistors were simulated using their S parameters at cryogenic temperature, and special attention was paid to develop adequate models of the passive components (resistors and capacitors). For example, the capacitor models take into account series resonance as well as the first parallel resonance and the series resistance. The model consists of a series R-L-C circuitry with parallel R-C and the values were chosen to fit the manufacturer S-parameters data. In order to improve the stability and the input match, inductive feedback is provided by bond wires from the transistor source to the ground, together with resistors in drain bias paths. The bonding wire model was developed using 3D EM simulation HFSS CAD software [5].

The most critical part 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 for the best noise performance of the transistors. The input stage uses mainly a low impedance line, followed by a high impedance line. We also use a tuning stub, to slightly increase the bandwidth, which is included in the transistor gate bias line (Figure 1). This input stage was built as a separate test unit and measurement with a TRL calibration helped us to adjust the location of the capacitor in the input circuitry for the optimum performance of the entire amplifier by changing the bypass capacitor location (±1 mm). The inter-stage and the final-stage were optimised for maximum gain, gain flatness and for 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 - therefore it is ideal for applications in thermally changing environments. We use chip ATC capacitors of series 100A 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 (Figure 2 shows the amplifier with the sidewall removed).

We chose the option of having a cooled isolator at the input of the amplifier. On one hand this facilitates the design of the amplifier input circuitry, its input reflection coefficient is required to be only less than -5 dB. But on the other hand the insertion loss of the isolator adds about 10% of the noise when connected to the amplifier input.

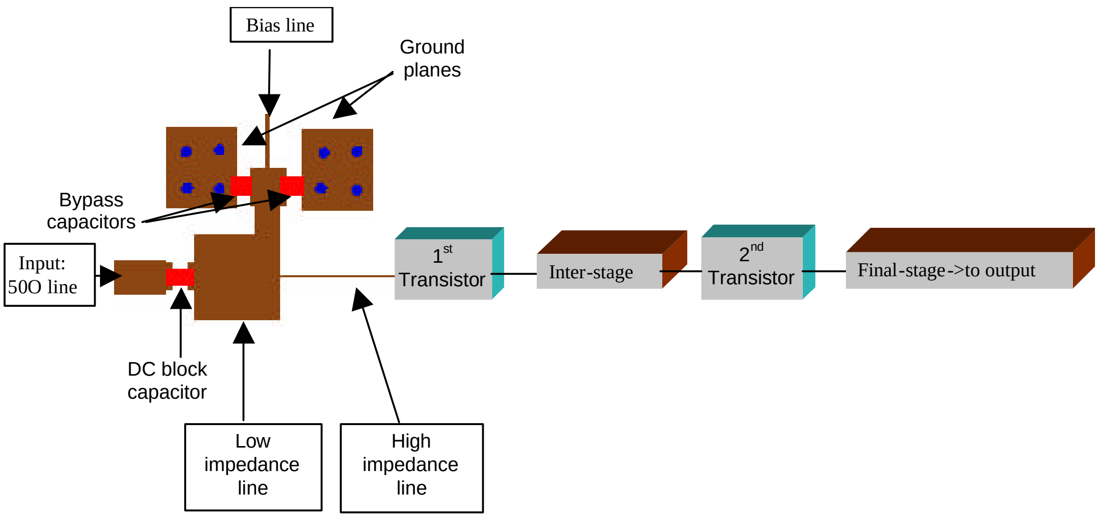

Figure 1. The amplifier block diagram and the input circuitry schematic.

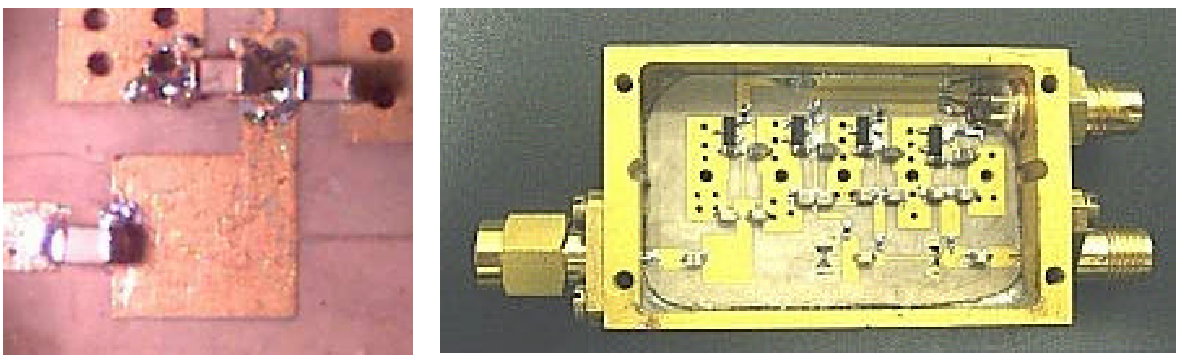

Figure 2. The picture of the first amplifier prototype, to the right, with the input circuitry magnified, at the left. The wall separating the RF and bias parts of the amplifier has been removed. The amplifier outer dimensions are 60mm x 26mm.

Results

The results of the tests in comparison with the ADS simulation are summarized in Figure 3. At the room temperature (293K) the lowest noise temperature measured is 35K (noise figure of 0.56 dB) and the amplifier gain is 26 dB. When cooled to 12K, the noise temperature of the amplifier is 2.8 K (noise figure of 0.045 dB) and the gain is 28 dB.

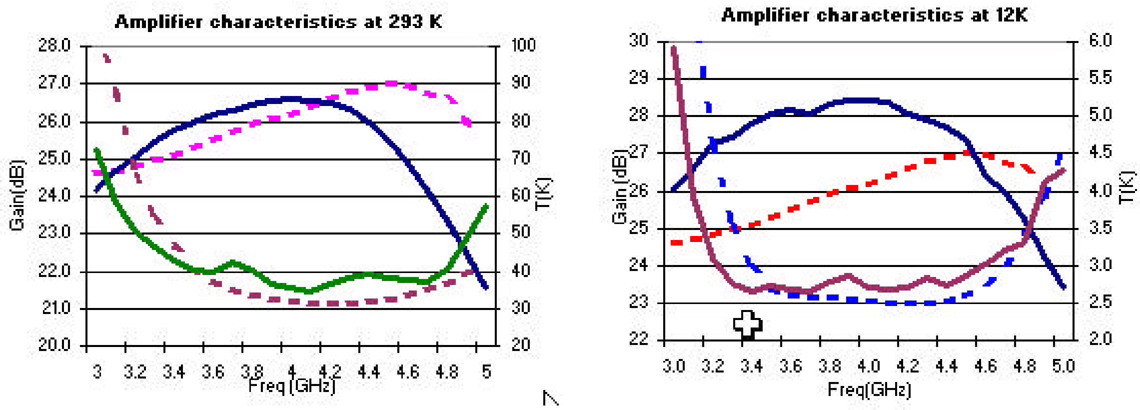

Figure 3. Simulations and measurements; the simulations plots are in dashed lines. The axis for the gain (upper curves) is on the left and for the noise temperature (lower curves) – on the right for both plots.

Input match S11 is less than –5 dB, as expected, and the output match S22 is less than –13 dB. At the cryogenic temperature (12K), the measurement of the amplifier together with the cooled isolator gives a noise temperature of about 3K, with a slightly narrower bandwidth, which is still quite acceptable. 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 better to what could be achieved with an amplifier without isolator. The gain value increases of about 2 dB at the cryogenic temperature. The agreement between the simulation and the measurement is very good, which is in part due to very accurate cold S parameter data for the transistors extracted by I. Angelov using M. Pospieszalski noise model for the transistor [6].

Noise Temperature Measurement Accuracy Analysis

Two methods were used to measure noise at cryogenic temperatures: the variable load temperature (VLT) method and the cold attenuator (CA) method, both employ so called Y-factor measurement technique. To determine the noise temperature of a device under test (DUT) using Y-factor method, the procedure is to connect matched loads at different temperatures (T_{hot}, T_{cold}) at the input of the DUT, and to measure the output powers. As the DUT is assumed to be linear, the two measurement points are sufficient. The noise temperature T_e is then estimated as [7, 8]:

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

VLT method is a direct Y-factor measurement with a 50-Ohm load together with a heater installed inside the cryostat and connected directly through a small piece of stainless steel coaxial cable (for thermal insulation) to the input of the amplifier (Figure 4). When the heater is OFF, the load is almost at the ambient cryogenic temperature 12K (measured by a precision thermometer), whereas when the heater is ON a temperature of 40K can be reached.

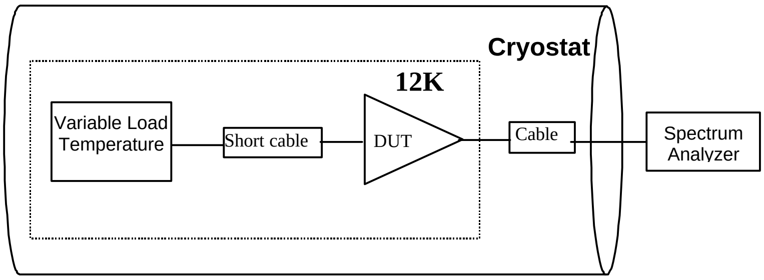

Figure 4. Variable Load Temperature Method

In our test bench the CA method uses a noise diode HP346B with 15dB ENR, together with a noise figure meter HP8970B, and 23 dB attenuators before the amplifier under test (Figure 5). The noise source is a 50 Ω load at 293K when OFF, so the amplifier sees at its input via 23 dB cold attenuator an equivalent T_{cold} of 12K. When the noise source is ON, the equivalent temperature is of 9000K at the output of the noise source or T_{hot} of 50K at the input of the amplifier. The attenuators reduce the effect of the input cable (its noise temperature is only roughly estimated, and therefore its contribution is significantly reduced by this attenuation). They help also to improve the match of the noise source with the DUT (the noise source impedance varies significantly between ON and OFF, without attenuators, variations in noise measurement are ±1K, whereas with attenuators, variations in noise measurements are only ±0.1 K).

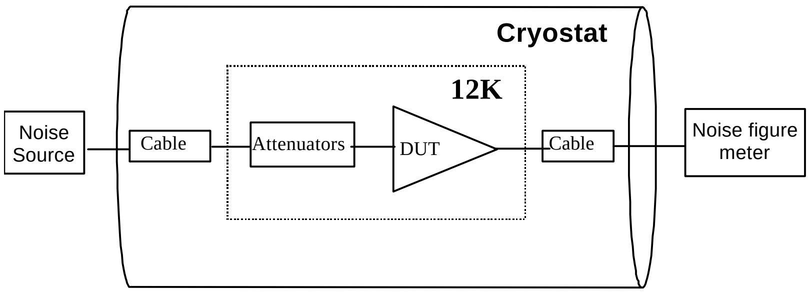

Figure 5. Cold Attenuator Method

Analysis of the measurement accuracies was done using MathCAD [9]. Different elements in the measuring circuitry were taken into account (noise source ENR, input cable influence, attenuators losses and temperature) and the influence of each element was estimated. Assuming that the errors coming from these different elements are uncorrelated, we adopted as a good approximation of the overall error a square root of the sum of the individual errors squared. Nevertheless, an even better estimation would be achieved by running a Monte-Carlo simulation, i.e. to assume that each source of measurement error is distributed in a Gaussian, bell-shaped, probability distribution. The major contribution in measurement error common for both methods is the accuracy of the temperature sensor, originally it was ±0.5K, and so the sensor was calibrated down to ±20mK [10]. The network analyser that measures the output power has a resolution of 0.05 dB giving an error of about ±0.25K. In the CA method the other major sources of error are the accuracy of the noise source ENR (15dB ± 0.1dB), which gives an error of ± 0.39K, and the accuracy of the loss measurement (±0.15 dB) of the input cable and the attenuators giving an error of ±0.50K. Several other sources of error have to be taken into account: mismatches, connectors, instruments uncertainty, gain instability, input cable physical temperature. The estimations are difficult but we found that their partial influences are quite small and the overall value for all of these error contributions is of ± 0.30 K.

Finally, for the VLT method, the accuracy of the measurement is ±0.40 K, and for the CA method it is ± 0.74 K. Tables 1 and 2 summarise major errors for both methods. Figure 6 shows the results of the noise temperature measurements for the two methods; the measurements are consistent and the measured data agreement is excellent.

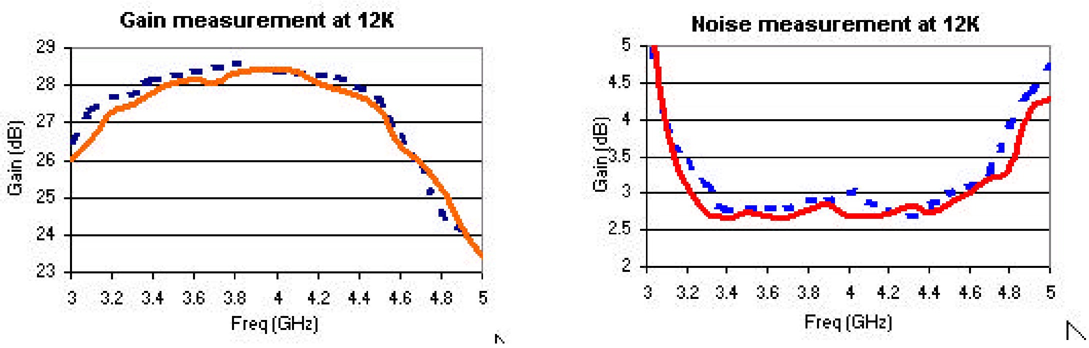

Figure 6. Comparison between VLT and CA method: VLT results are in dashed line.

Table 1. Error budget for noise measurements with **the cold attenuator method**

Parameter	*Nominal value*	*Tolerance*	*Resultant error in Te, K*
Noise diode ENR	15.0 dB	±0.1dB	±0.39 K
Losses (attenuators, input cable)	23.0 dB	±0.15 dB	±0.50 K
Cold attenuator temperature	12.0 K	±0.02 K	±0.02 K
Y factor	7.0 dB	±0.05dB	±0.23 K
Others (mismatch, gain variation, input cable)			±0.30 K
Total error			**±0.74 K**

Table 2. Error budget for noise measurements with **the variable load temperature method**

Parameter	*Nominal value*	*Tolerance*	*Resultant error in Te, K*
Hot load temperature	40 K	±0.02 K	±0.02 K
Cold load temperature	12 K	±0.02 K	±0.02 K
Y factor	4.6 dB	±0.05dB	±0.27 K
Others (mismatch, gain variation, input cable)			±0.30 K
Total error			**±0.40 K**

Conclusion

A 3.4-4.6 GHz low-noise 2-stage amplifier based on GaAs HEMT transistors was designed and the prototype was tested at room temperature and at 12 K as part of our work on 3-mm Radio Camera Project for Onsala Space Observatory. The measured amplifier performance, the gain and the *lowest* noise temperature, are 26 dB and 35 K at 293 K and 28 dB and 2.8 K at 12 K and represent the state of the art for this frequency range. The power consumption for optimum noise performance is of 12 mW. The amplifier design was done using ADS and special attention was paid to use accurate cold S-parameters, to model the passive components and the matching circuitry correctly. The amplifier input circuit was also built separately, that helped us considerably in tuning the amplifier. The measured performance of three fabricated amplifiers are completely consistent and in excellent agreement with the modelling. Two methods of noise measurement, the variable temperature load and the cold attenuator, have been used and compared and the overall accuracy of the measurement estimated for both methods to be ±0.40 K and ±0.74 K respectively. We expect further improvement of the amplifier performance by replacing GaAs transistors with InP HEMTs, yielding the amplifier noise temperature to go as low as 2K.

Acknowledgements

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References

[1] D.F.Wait “*Considerations for the precise Measurement of Amplifier Noise*”, National Bureau of Standards note 640, 1973.

[2] J.E.Fernandez “*A Noise-Temperature System using a cryogenic Attenuator*”, TMO Progress Report 42-135, 1998.

[3] J.D.Gallego, I.L.Fernandez “*Definition of measurements of performance of X band cryogenic amplifiers*”, Technical Note ESA/CAY, 2000.

[4] Advanced Design System version 1.3, Agilent Technologies.

[5] High Frequency Structure Simulator version 5.6, Agilent Technologies.

[6] N. Wadefalk & I. Angelov, Private Communication.

[7] “*Fundamentals of RF and Microwave Noise Figure Measurements*”, Agilent technologies Application Note 57-1

[8] “*Noise Figure, Measurement Accuracy-The Y-Factor method*”, Agilent technologies Application Note 57-2.

[9] MathCAD 2000 Professional by MathSoft Inc.

[10] ”*Temperature Measurement and Control*”, Lakeshore Cryotronics, p. A-24, 1995.