Cryogenic LNA Characterization with SIS Junction as a Noise Source

E. Sundin, A. Pavolotsky, C. Risacher, V. Vassilev and V. Belitsky

***Abstract*—Radio astronomy heterodyne receivers based on SIS mixers and hot electron bolometers always use cryogenic low-noise IF amplifiers. Modern HEMT-based amplifiers have the noise temperature of a few Kelvin. In order to have good understanding of the system noise contribution it is of interest to characterize IF amplifier noise accurately. Another important reason why one should know the noise temperature of the amplifier more accurately is that this is the main parameter, which drives the amplifier design and thus is of a greater importance for cryogenic amplifier development. Widely used cold attenuator (CA) method includes several unrecoverable sources of errors such as losses in the coaxial cables, temperature dependences, temperature gradients and accuracy in measurement of the attenuators physical temperature. The error of the CA-method is of the order of ±0.5 Kelvin. This can be as much uncertainty as almost 30% of the measured amplifier noise temperature.**

This paper describes a way to improve the accuracy of the LNA characterization by using a SIS-junction as a source of shot-noise. When SIS junction biased in the linear part above the gap, the equivalent noise temperature of the shot-noise is dependent on the bias voltage and the fundamental physical constants only. The result is an extremely well defined source of noise. However, the most challenging part of this is the losses due to matching to a 50 Ω coaxial line, which is typical interface of an LNA. In order to reduce the complexity of the design and remove the need of matching network, the SIS junction should be manufactured with normal state resistance $R_n \equiv 50\Omega$. Additionally, in order to provide a wideband operation of such precession noise source a special matching circuitry is necessary to ensure the source impedance will be matched within desired frequency band of 3 - 10 GHz.

***Index Terms*— Amplifier noise, Cryogenic electronics, Noise measurement, Superconductor-insulator-superconductor devices**

I. Introduction

In most radio astronomy front-ends cryogenic low noise (LNA) HEMT amplifiers are used as a second IF stage following the superconducting mixer. For observations up to around 100 GHz HEMT can be used as a front-end. Noise temperature of the IF amplifiers (4-8 GHz) in use is typically about 5K and depending on available transistors 2-3K can be achieved [1].

The purpose of this project is to increase the accuracy for the noise characterization of the cryogenic amplifiers that is developed and built by our group. It can be used to characterize one amplifier to be a reference to compare or calibrate the usual measurement setup or directly used for amplifier characterization. The current method in use is the cold attenuator and [2] shows that the accuracy is about ±0.74K. Considering that the measured values are expected to be in the range of 4-5 K, this error is quite large to give desirable accurate measurements. Y-factor method used to make the characterization employs a noise source placed outside the cryostat; with the use of an attenuator at the amplifier input the influence of errors in loss estimation in cabling to the amplifier is reduced. Another method considered in [2] is the hot-cold method employing a variable temperature load placed inside the cryostat. The Y-factor is used also here but the physical temperature of the input load is changed inside the cryostat. Better accuracy, about ±0.40K, is estimated [2] but the change between the hot and cold states is more time consuming procedure as well as the loss with the thermal gradient in the cable connecting the load and the amplifier under the test.

The current project is based on using a superconducting tunnel junction, SIS, as source of shot-noise. Physical constants and the bias voltage define the power of the shot-noise, and thus the equivalent load temperature is defined precisely when the junction is operated in the linear region of its current-voltage characteristic above the gap voltage. The advantage of this idea compared to the usual hot-cold method is that all parts have the same physical temperature and thus no thermal gradient affecting the accuracy is presented, see Fig. 1. Consequently, the SIS noise source can be directly connected to the amplifier, which reduces possible errors in estimations of cable losses and connectors, also the change between hot and cold load occurs much quicker. Since the structure is based on superconductivity the operating temperature must be well below 9K since Niobium-based SIS is used. We have chosen dip-stick measurements, when the source and amplifier is immersed into liquid Helium providing quick method with well-known physical temperature, though the size and mechanical design of Device Under Test (DUT) is strictly limited to the Dewar's neck. In comparison the cryostat

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method requires a cryocooler supporting 4K instead of our current 12K, but the mechanic design is less restricted.

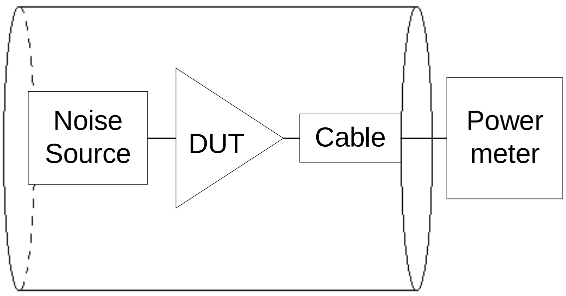

Fig. 1. Schematic of Y-factor measurement setup, where the source is placed close to the device under test and at same ambient temperature as the DUT.

II. Source

The concept of this work is to use a SIS junction as the source of noise. The technique has been used since beginning of 90's as a built-in IF diagnostic system for the SIS receivers [3]. Instead, we use the SIS junction primarily for the purpose of generating noise to be able to perform accurate Y-factor measurements. Since this is the main purpose, the design can be optimized to reach as good as possible coupling between the junction and the output connector without trade-offs. When a junction is biased in its linear region, above the gap voltage, the current fluctuations when $hf << eV_0$ is given by [4] as

$$\left\langle i^2 \right\rangle = 2 \cdot e \cdot I_{bias}(V_{bias}) \cdot B \cdot \coth\left(\frac{e \cdot V_{bias}}{2 \cdot k \cdot T}\right) \quad (1)$$

where e is the electron charge, V_{bias} is the DC voltage over the junction, B is the bandwidth, k is Boltsman's constant and T is the ambient temperature. At low temperature and in the linear region the coth-term becomes unity. The shot-noise generated by the junction when biased in the linear region is defined by

$$Te = \frac{e \cdot V_{bias}}{2 \cdot k}. \quad (2)$$

This results in a linear slope of the noise temperature of Te≅5.8 K/mV. Variable load temperature Y-factor measurements can be done with the source temperature of about 20-60 Kelvin for the "cold load" bias slightly above the gap and for the "hot load" at a higher voltage, up to 10 mV. The design has been done to be reasonable insensitive to variations in the processing of the SIS structure and mounting the sample in the holder. The SIS structures are produced in-house with Nb-based tri-layer thin film processing. Substrate is crystal quartz to ensure good thermal properties since the bias point will be higher than normally used in mixers, see Fig. 2.

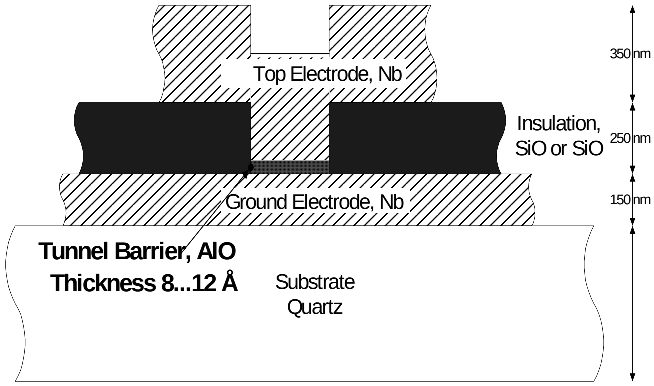

Fig. 2. Cross-section of a SIS junction used as source. Structure is built on quartz substrate with thickness of 150 micrometer. Layer thickness starts at 150 nanometer and increases with 100 nm per layer.

III. Design

A. Electrical design

Considering the chip itself, the first layout was done in Agilent ADS where tuning and tests of different approaches are quick and easy. In the schematic mode in ADS no care is taken about coupling between the closely spaced components. As a complement, HFSS was used to get more accurate model of the circuit. Results from HFSS were exported to S-parameters and used in ADS since the junctions parasitics have to be taken in to account. The reason is that the layout needed to be divided into two parts since the junction should be embedded inside the model, it is also quicker to smaller simulations and combine them when a change is done only in one part of the circuit instead of redo the simulation for the complete structure. To make the source matched to the standard 50 ohm, the SIS junction is designed to have a normal state resistance (R_n) of 50 ohm. This solution with such high R_n was chosen instead of designing a matching network for a typical R_n in the range 5-15 ohms. Thus, no matching of the impedance needs to be done, and the circuit layout will consist of a fewer components and so both design/simulation will be simpler and more accurate. The actual R_n of the manufactured junction compared with the designed can differ a bit. In general, a common solution to increase the R_n is thermal annealing at 130-150 degrees Celsius. Aiming at an R_n slightly lower, say 45 ohm, the sample can be heated in a controlled way until a good result is achieved.

First idea was to have a simple chip and an external bias network, but small variations in connections from bond wires seemed to have much influence on the performance and required precise control over bonding. It was therefore decided to remove the bias network such that the bond wires to be of less influence, see Fig. 3. The chip size become 2.5 mm x 5.5 mm and is connected to the SMA connector by joining the connector against the chip with pressing pure indium in between. The same method is used for the connection to the ground. Biasing is done with 4-wire method and is DC current controlled.

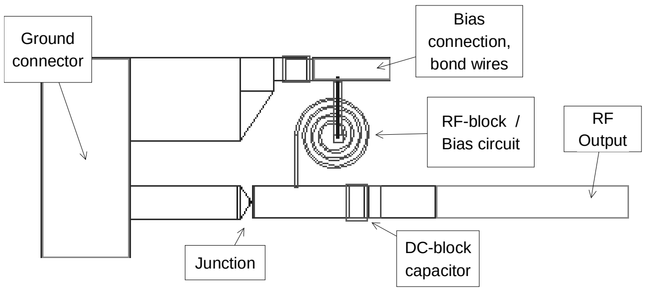

Fig. 3. Layout of the chip. To reduce the influence of shape and exact placement of bond wires, parts of the bias network is placed on the chip. This is the reason why the inductor is integrated on the chip.

B. Dip-stick

For the measurements to be done with the dip-stick the allowed dimensions were limited by the opening diameter of the Dewar, which is 50 mm, some margin is obviously needed. structure to be cooled should preferable be light to reduce the consumption of liquid helium. This limited also the design of the amplifier to be measured, and the current design had to be modified to fit in to this size. The probe part of the dip-stick is made to be flexible in sense of further changes or to be used in other projects as well if needed.

IV. Measurements

The measurement setup consists of current source, voltmeter, power meter (power meter or spectrum analyzer) and a computer (see Fig 4) with GPIB interface to control the setup. For the first tests a spectrum analyzer was used to measure over the spectrum (3-9 GHz), also a power meter with a band-pass filter for 4.0-4.5 GHz were tested. Designed bandwidth for the amplifier is 4-8 GHz. Corrections for losses and noise contribution in the cables and the room temperature amplifier were done. More care should be taken to take the linearity and eventually offsets in to account, also R_n of the used chip was 37 ohm instead of the aimed 50 ohm and no correction were done for that in this first test.

Measurements done with the spectrum analyzer has the advantage to show the whole band for the amplifier. With the drawback of unreliable results since each point has small bandwidth and even with averaging results varies quite a lot. The results with use of a power meter were much more stable since a band-pass filter of 500 MHz was used. For now only a filter with center frequency close to the edge of band were available, instead of in the middle, which would give more reliable value of gain and noise temperature. A drawback with this approach is clearly that different filters is needed depending on which frequency should be measured.

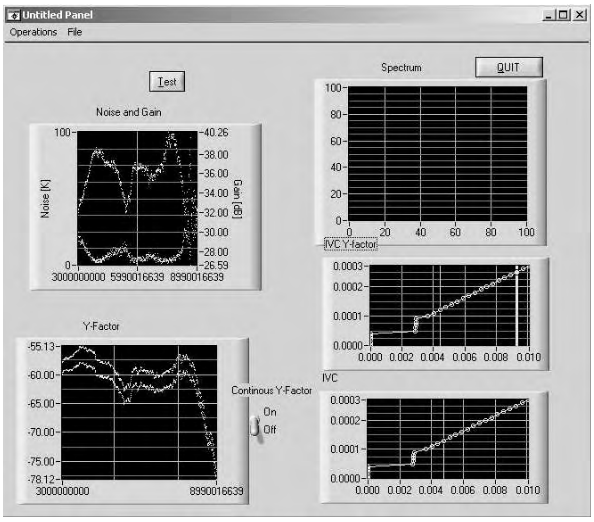

Fig 4. Print screen from the program written in LabWindows. Graphs shows the calculated DUT gain and noise temperature, the measured spectrum from the analyzer and the IVC of the junction with the used bias points used for the cold and hot load.

V. Conclusion

A new method for characterization of cryogenic low noise amplifiers were presented and tested experimentally. According to the first measurements the method seems promising, although much more care should be taken to provide and keep high accuracy of characterization.

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