SIS junction as a microwave noise source

Hirofumi Inoue$^{1,2}$, Takashi Noguchi$^1$ and Kotaro Kohno$^2$

$^1$National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588
$^2$Institute of Astronomy, the University of Tokyo, 2-21-1 Osawa, Mitaka, Tokyo 181-0015

E-mail: h-inoue@ioa.s.u-tokyo.ac.jp

Abstract. Cooled low noise amplifier (LNA) is used as the first or second component of receiver system in radio astronomy. It is developed all over the world to improve its noise. Noise temperature is one of the most important parameters of LNA because it governs the observation time. It is usually measured by inputting two reference signal which have different power each other and measuring the responses. For accuracy, the power of these reference signals is required to be close to the noise of the LNA. In the conventional method output of a Avalanche diode is attenuated to 1/100 by a cold attenuator and used as a reference signal. In this method the error caused by the attenuator and the cable between the Avalanche diode and LNA is too large (a few 10 %) and another accurate noise measurement method is required.

In this research we propose a new method using Superconductor-Insulator-Superconductor junction (SIS) as a reference signal. When biased, SIS generates small shot noise that is proportional to the bias voltage so it can be used as a reference signal that make an accurate noise measurement possible (a few % error). First, SIS and SIS housing is designed and fabricated for the shot noise to transmit without any loss and reflection. Then, noise temperature of the LNA is measured by using the conventional method and SIS shot noise method and compared. As a result, there was difference and it was shown that the capacitance of SIS is one of the candidate cause.

1. Introduction

Radio astronomy have studied planet, star formation and evolution of galaxy from spectroscopic observation using receiver. The observation time took depends on the noise of the receiver, usually expressed by noise temperature, so it is important to decrease it as low as possible. Cooled low noise amplifier (LNA) is the first or second component of the receiver. The noise temperature of the LNA is recently so low that the measurement error is relatively too large.

The noise temperature is usually measured by Y-factor method. In Y-factor method, two different reference noise (called hot and cold load) is input into device under the test (DUT) and the output of the DUT are compared. The reference noise should be as small as the noise of the DUT because too large reference noise will cause saturation problem. The most popular method for noise measurement of the LNA is cold attenuator method (CAT), which uses Avalanche diode with attenuator as a reference noise. When the Avalanche diode is on, it generates the equivalent temperature of 9000 K and the attenuator decreases it to 1/100 (90 K) and when the Avalanche diode is off, the equivalent temperature is the environment temperature 300 K, so the DUT sees 3 K as a cold load. In CAT, the unaccuracy due to the loss of the input cable and the attenuator and to the temperature of the attenuator is large, for example, 1.4 K ± 1.23 K ([1]). Another noise measurement method is variable temperature load method (VTL), which uses a
load with a heater as a reference noise. The measurement unaccuracy of this method is small but it is difficult to know whether the internal temperature of the load is same as the measured temperature and it takes time until the temperature of the load become stable. So reference noise which does not depend on physical temperature and generates enough small noise power directly is required.

Superconductor-Insulator-Superconductor junction (SIS) will be a good reference noise. When the insulator between the two superconductor is very thin, the quasi-particle can go through it as a tunnel current. The current flow is not continuous but discrete and independent so it generates shot noise. Above the gap voltage SIS shows linear current-voltage characteristics and theoretically the equivalent noise temperature of shot noise is \( T_N = 5.8V \) and it is about 25-200 K for \( V=5-30 \) mV. This means that SIS can be used as a good reference noise which generates small power noise directly and does not depend on physical temperature.

In this study, we propose a method using SIS as a noise source for LNA noise measurement in the microwave region. The unaccuracy of SIS shot noise method is estimated \( \pm 0.11 \) K if the condition would be the same as [1]. Woody had already measured intermediate frequency (IF) system noise temperature of receiver system by SIS shot noise method but he didn’t cared impedance matching [2]. Sundin took into account impedance matching and tried SIS shot noise method, but the measured noise temperature showed SIS bias voltage dependence and the cause is not yet known [3].

2. Theory

According to the quantum tunneling theory, the shot noise generated by the quasi-particle tunneling through the SIS junction is following [4]:

\[
\langle i^2(\nu) \rangle = e \left[ I \left( V_0 + \frac{h\nu}{e} \right) \coth \left( \frac{(eV_0 + h\nu)}{2kT} \right) + I \left( V_0 - \frac{h\nu}{e} \right) \coth \left( \frac{(eV_0 - h\nu)}{2kT} \right) \right]
\]

In low frequency limit \( h\nu \ll eV_0 \), this becomes:

\[
\langle i^2 \rangle = 2eI(V_0)B \coth \frac{eV_0}{2kT}
\]

In high voltage limit \( kT \ll eV_0 \), this becomes:

\[
\langle i^2 \rangle = 2eI(V_0)B
\]

In this research, \( \nu = 4 - 8 \) GHz, \( V_0 > 4 \) mV, \( T = 4 \) K, so it can be said it is low frequency and high voltage limit. SIS junction shows linear voltage-current characteristics \( I(V_0) = V_0/R_n \) above the gap voltage:

\[
\langle i^2 \rangle = 2eB \frac{V_0}{R_n}
\]

When a load that matched with SIS junction is connected with SIS junction, the power \( P \) the load receives is:

\[
P = \frac{i^2R_n}{4} = \frac{2eBV_0R_n}{R_n} = \frac{eBV_0}{2}
\]
This is

\[ T_n[K] = \frac{e}{2k}V_0 \]  
\[ = 5.8V_0 \text{ [mV]} \]  

in terms of equivalent noise temperature. This means SIS junction can be used as a voltage controlled reference noise.

3. conventional method (CAT)

3.1. measurement set up

The measurement configuration of CAT is shown in figure 1. The noise temperature of LNA \( T_e \) is:

\[ T_e = \frac{T_{sys} - (L_1 - 1)T_1 - (L_2 - 1)T_2L_1 - \frac{(L_3 - 1)T_3L_1L_2}{G} - \frac{T_{rec}L_1L_2L_3}{G}}{L_1L_2} \]  

where \( T_{sys} \) is the system noise temperature, \( T_1, L_1 \) are the physical temperature and the loss of the input cable, \( T_2, L_2 \) are the physical temperature and the loss of the cold attenuator, \( T_3, L_3 \) are the physical temperature and the loss of the output cable, \( T_{rec} \) is the noise temperature of the receiver system, \( G \) is the gain of the LNA. The unaccuracy of the components after the LNA is divided by \( 1/G \), so they don’t affect so much. For accurate measurement, the loss of the input cable and the cold attenuator must be known. The loss of the input cable and the cold attenuator cooled to 4 K were measured by network analyzer. The LNA measured was Nitsuki model 9891 and its specification is shown in table 1. The noise temperature of the LNA with and without isolator were measured. The isolator suppress the reflection at the input of the LNA and bias SIS in SIS shot noise method.

3.2. result

The result is shown in figure 2. Without the isolator, the frequency characteristics of the noise temperature is smooth and almost the same as the specification. But with the isolator, there was ripple of which the amplitude is 1 K and the frequency is 1 GHz. This ripple can be explained.
| Specification                        | Value       |
|-------------------------------------|-------------|
| Frequency                           | 4-8 GHz     |
| Gain                                | over 30 dB  |
| Noise temperature                   | under 8 K   |
| Input return loss                   | under -5 dB |
| Output return loss                  | under -15 dB|
| Maximum input power                 | under -15 dB|
| P1 dB                               | over -30 dBm|

Table 1. specification of LNA Nitsuki model 9891.

![Figure 2. The noise temperature of the LNA with (red) and without (green) the isolator at 4 K.](image)

by the multiple reflection between the isolator and the LNA and the noise temperature of the LNA with the isolator $T'_e$ can be written as:

$$T'_e = \left( \frac{1}{G_{iso}} - 1 \right) T_{iso}^{\text{physical}} + \frac{1 - S_{11}^{\text{amp}} S_{22}^{\text{iso}}}{G_{iso}} | T_{noise}^{\text{amp}} |$$

(11)

where $G_{iso}$ is the gain of isolator, $T_{iso}^{\text{physical}}$ is the physical temperature of the isolator, $S$ is scattering parameter and its upper index means the isolator and the LNA and $T_{noise}^{\text{amp}}$ is the noise temperature of the LNA. For the normal temperature measurement, the frequency characteristics of the noise temperature of the LNA with the isolator can be explained by this formulae (figure 3).

4. SIS shot noise method

4.1. SIS

The shot noise generated by SIS must be transmit to the LNA without loss and reflection for accurate noise measurement so SIS must satisfy impedance matching condition. Thus SIS impedance was designed to be 50 Ω. SIS impedance is determined by its barrier and can be controlled by the oxidation condition. The junction size is $4 \times 4 \mu m^2$ for easy fabrication and the oxidation condition was determined according to [5].
Figure 3. The noise temperature of the LNA with the isolator at the normal temperature. The red line is measured data and the green line is formulae (11).

4.2. measurement set up

When the LNA receives the shot noise from SIS, the output of the LNA is

\[ P_{\text{out}}(V_0) = GkB(T_{\text{in}} + T_e) \]  

(12)

where \( V_0 \) is the bias voltage, \( T_{\text{in}} \) is the equivalent temperature of the input signal into the LNA and \( T_e \) is the noise temperature of the LNA. If the shot noise is \( T_n = 5.8V_0 \) as the theory, the output is

\[ P_{\text{out}}(V_0) = GkB(5.8V_0 + T_e) \]

(13)

\[ = 5.8GkB V_0 + GkB T_e. \]

(14)

Thus, the LNA noise temperature \( T_e \) can be known by measuring the output power of the LNA dependence on the bias voltage \( P(V_0) \). The measurement set up of SIS shot noise method is shown in figure 4.

4.3. result

The result measured by SIS shot noise method is shown in figure 5. It is very different from the result measured by CAT, especially in the higher frequency, so we judged that there are some nonideal things happened in SIS shot noise method.

The ratio between the results of SIS shot noise method and CAT \( T_e' / T_e \) is

\[ \frac{T_e'}{T_e} = \frac{1 - |\Gamma_{\text{NS}}S_{11}^{\text{DUT}}|^2}{1 - |\Gamma_{\text{NS}}|^2} \]

(15)

where \( \Gamma_{\text{NS}} \) is the reflection coefficient of SIS and \( S_{11}^{\text{DUT}} \) is the scattering parameter of the LNA with the isolator.

First, an effect of the capacitance that SIS itself has was considered. The ratio between SIS shot noise method to CAT is shown in figure 6 left. The specific impedance of SIS \( C_S \) 40-100 fF/\( \mu \)m\(^2\) is calculated [6]. Under 6 GHz, some of \( C_S \) can explain the measurement, but above 6 GHz they can’t.

Second, series inductance was also considered. The ratio \( T_e' / T_e \) when inductance \( L = 1, 2, 3 \) nH and \( C_S = 60 \) fF/\( \mu \)m\(^2\) is shown in figure 6 right. When \( L = 2 \) nH, the measurement can be explained. We are investigating this inductance candidate now.
5. conclusion
The LNA noise temperature was measured by a new method using SIS as a reference signal. The result was compared with that by a conventional method. They were different, especially in the higher frequency. One of the cause is the capacitance of SIS itself and series inductance.

Acknowledgement
The authors would like to thank the members of the ALMA Band 10 group at NAOJ for their fruitful discussion and providing measurement instruments.

References
[1] Wadefalk N, Mellberg A, Angelov I, Barsky M E, Bui S, Cheumas E, Grundbacher R W, Kollberg E L, Lai R, Rorsman N, Starski P, Stenarson J, Streit D C and Zirath H 2003 IEEE Transactions on Applied Superconductivity 17 343
[2] Woody D P, Miller R E and Wengler M J 1985 IEEE Transaction on Microwave Theory and Techniques, 33 90
Figure 6. $T_e'/T_e$. left) The effect of the capacitance of SIS. The number plotted in the graph is the specific capacitance [fF/$\mu$m$^2$]. right) The effect of capacitance of SIS and the series inductance. The specific capacitance $C_S$ is 60 fF/$\mu$m$^2$. The number plotted in the graph is the series inductance [nH].

[3] Sundin E 2006 Technical report no. 2006:91, department of radio and space science with onsalaspace observatory, chalmers

[4] Rogovin D and Scalapino D J 1974 Ann. Phys. 86, 1

[5] Miller R E, Mallison W H and Kleinsasser A W 1995 IEEE Transaction on Applied Superconductivity, 5

[6] van der Zant H S J, Receveur R A M, Orlando T P and Kleinsasser A W 1994 Appl. Phys. Lett. 65 2134