Noise testing of the active and passive baluns for the ATA

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The ATA Low Noise Amplifier is connected to the feed with a quartz balun [1,2]. The balun converts the balanced signal from the feed to an unbalanced signal, which allows us to use a conventional single-ended LNA. This report describes noise testing of the quartz balun connected to the single-ended LNA (WBA13). The result is compared with similar tests of an active balun (WBAL2). Gain and noise have been tested for both these cases using a 200 ohm Variable Temperature Load (VTL) at 300, 77 and 12 Kelvin physical temperature. The result of two different baluns is also compared; one made on very low loss fused quartz, and the other on high thermal conductivity crystal quartz.

1. The test set-up

To be able to measure the noise of the balun and LNA we must inject a noise signal on the input of the DUT. Since the input is balanced and of a non-standard impedance, no commercial noise sources are available. To overcome this problem we had to design our own noise generator. This noise source is a 200 ohm thin film resistor on a 12*7.5 mm crystal quartz substrate (Fig 1). There are ultrasonically drilled holes through the substrate for a 200 ohm twin lead line to be connected to the resistor. The other end of the twin lead line goes to the DUT. For room temperature measurements, this resistor can be dipped in liquid nitrogen to change its temperature (noise power). At cryogenic temperatures however,

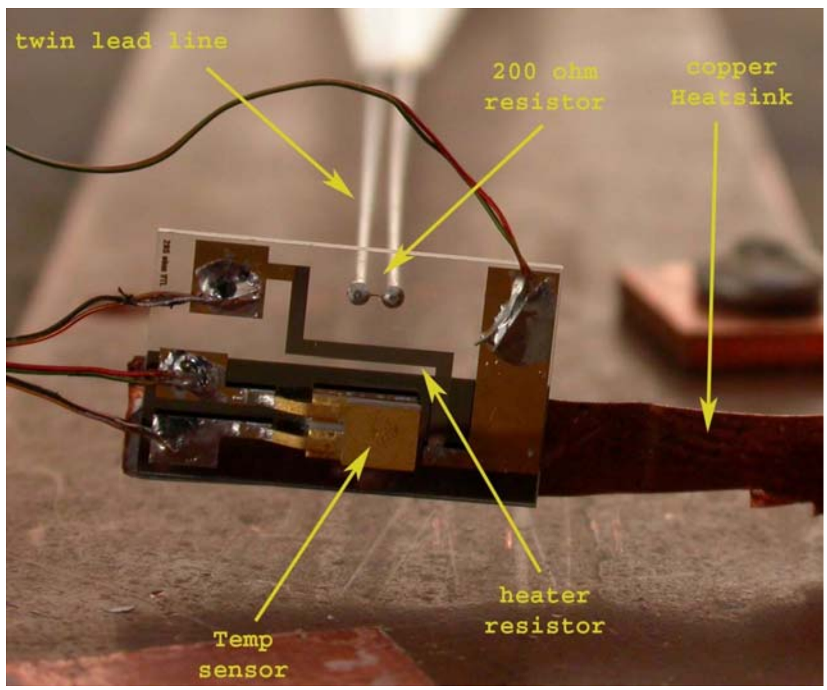

Fig 1. The 200 ohm VTL.

the temperature has to be changed by other means, and therefore there's also a heater resistor and a pad for a temperature sensor on the substrate. At low temperatures the thermal conductivity of crystal quartz is very high, which should make the temperature distribution along the substrate very uniform; i.e the sensor should measure the actual temperature of the 200 ohm resistor, even though it is not mounted on the resistor itself.
The VTL circuit was processed on 5 and 20 mil thick crystal quartz. The part of the twin lead line that goes through the substrate will have much lower characteristic impedance than the nominal 200 ohms, and therefore it is important to keep the substrate as thin as possible. This mismatch should give a ripple

in the measurement result as the impedance presented to the DUT varies around its nominal value. Simulations show that this ripple will be small even with the 20 mil substrate, and since it is more robust than the 5 mil one, all measurements in this report were done using the thicker substrate, except the room temperature measurements which used a special circuit with only the 200 ohm resistor on a 5 mils substrate. Figure 2 shows the VTL circuit connected to a 200 ohm, 2” long twin lead line followed by the balun and the LNA. The twin lead line consists of two 0.014” diameter silver plated stainless steel tubes.

2. Measurement results

The measurements were done at 300, 77 and 12 K physical temperature. The 12 K experiments were done in a large cryobox equipped with a CTI 350 cryocooler, while the 77 K measurements took place in a small Infrared Labs liquid nitrogen dewar. The 12 K dewar has a radiation shield with a temperature of 90 K, and the 77 K dewar has a 77 K radiation shield. However, where the balun sits in the 77 K dewar, there is an opening in the radiation shield and therefore it will “see” the 300 K walls surrounding it. Since the ATA dewar has a radiation shield that is at the same temperature as the balun, a copper foil enclosure were built for the balun to simulate the situation in the ATA dewar. Figure 3 shows the measurement set-up with this enclosure.

The active balun MMIC was mounted on a small copper plate together with the necessary external components (input matching network, biasing components, etc). The fact that there is no cover over the MMIC makes it sensitive to where it is located in the dewars. If it is surrounded by metal, feedback from output to input via a waveguide mode can cause gain peaks and in worst case oscillations. Normally high gain MMICs are mounted in a narrow cut-off cavity to avoid such problems, but as a first test the flat copper plate is sufficient (Fig 7). The result at 300, 77 and 12 K are presented in Fig 4-6 respectively, and the bias settings in Table 1. The graphs also include simulation results for the LNAs. This curve applies to both the single-ended LNA and the active balun, since theoretically they should have the same noise.

Fig 2. Test set-up with VTL, balun and LNA

Fig 3. Same test set-up as in Fig 2, but with the shield.

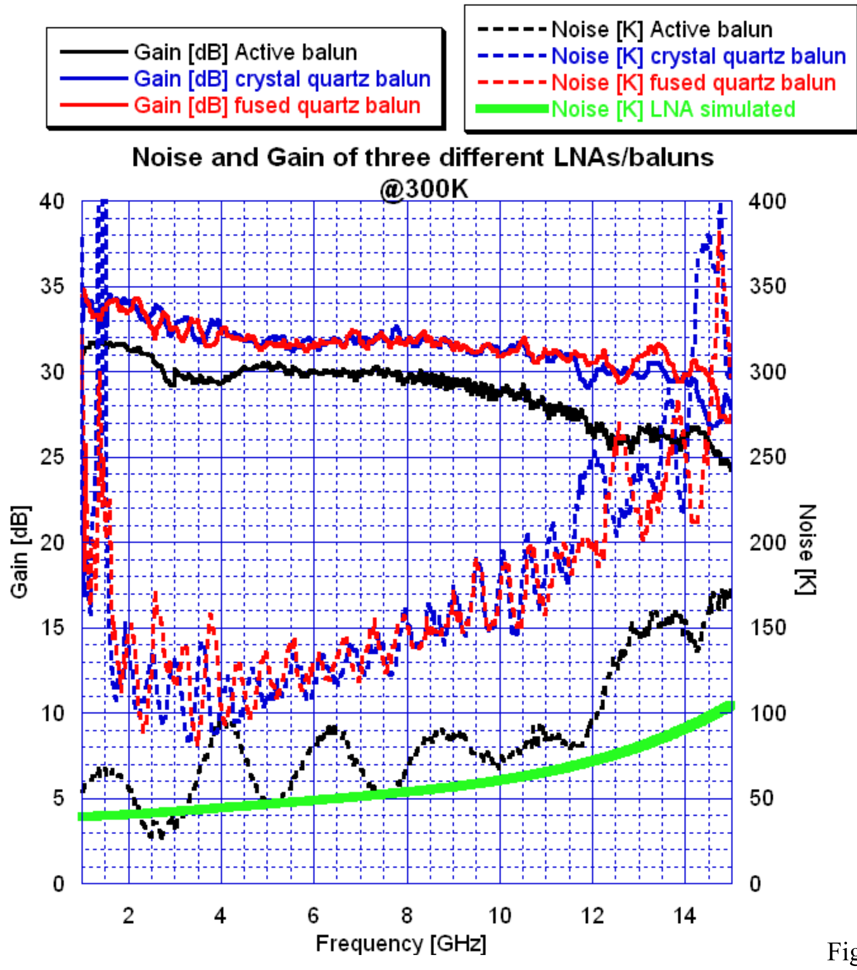

Fig 4. Test result at 300 K

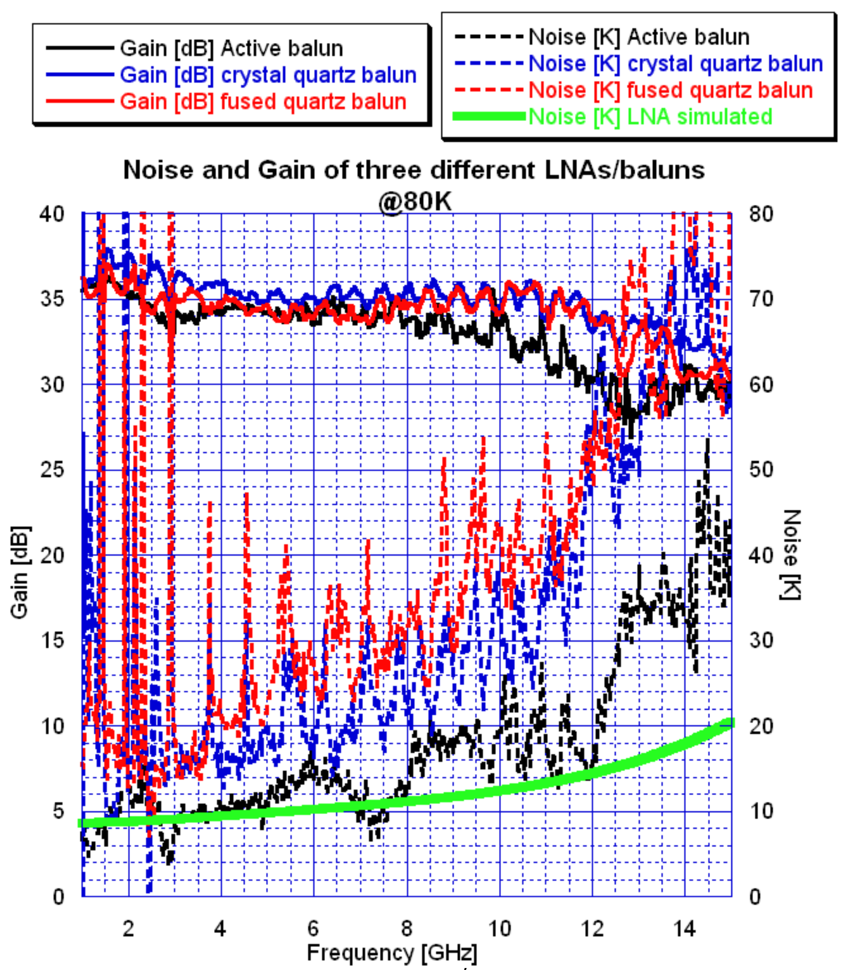

Fig 5. Test result at 80K

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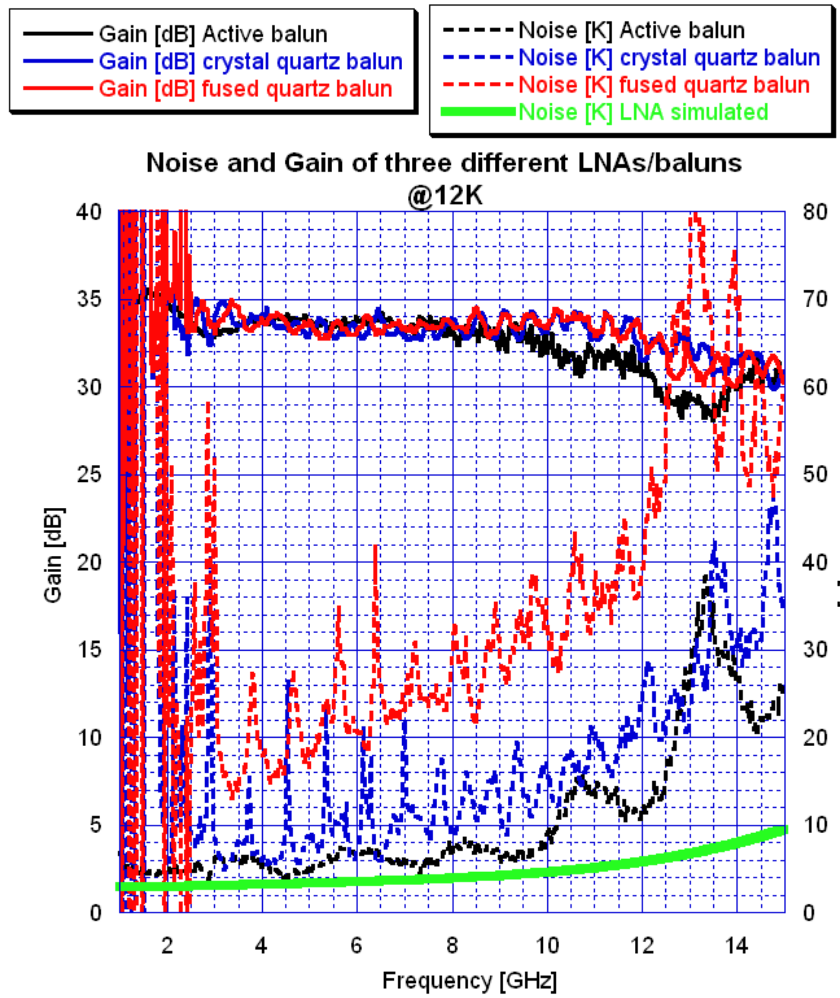

Fig 6. Test result at 12 K

All measurements are referenced to the 200 ohm resistor side of the twin lead line, i.e no compensation was done for losses in the 2” long line. One important piece of information is missing in the three noise graphs, namely the measured noise of the single-ended LNA. Unfortunately, for the moment we have no way of measuring this LNA, which has a 100 ohm microstrip input, at cryogenic temperature; however it has been measured at room temperature with very good agreement with simulations. Further, a coaxial 50 ohm module using the same MMIC has been measured at all three temperatures with equally good agreement with simulations. We believe that the maximum error of the simulated performance indicated in Fig 4-6 is less than 30% for WBA13.

	Vd [V]	Id [mA]	Vg [V]	V- [V]	I- [mA]	Pdc [mW]
Active balun @300K	1.80	100	0.132	-1.50	-50	255
Active balun @77K	1.60	74	0.155	-1.20	-40	166
Active balun @12K	1.40	64	0.180	-0.85	-31	116
Single ended LNA @300K	1.80	50	-0.077	n/a	n/a	90
Single ended LNA @77K	1.50	40	+0.082	n/a	n/a	60
Single ended LNA @12K	1.20	20	+0.025	n/a	n/a	24

Table 1. Bias conditions of the two LNAs at 300,77 and 12 K.

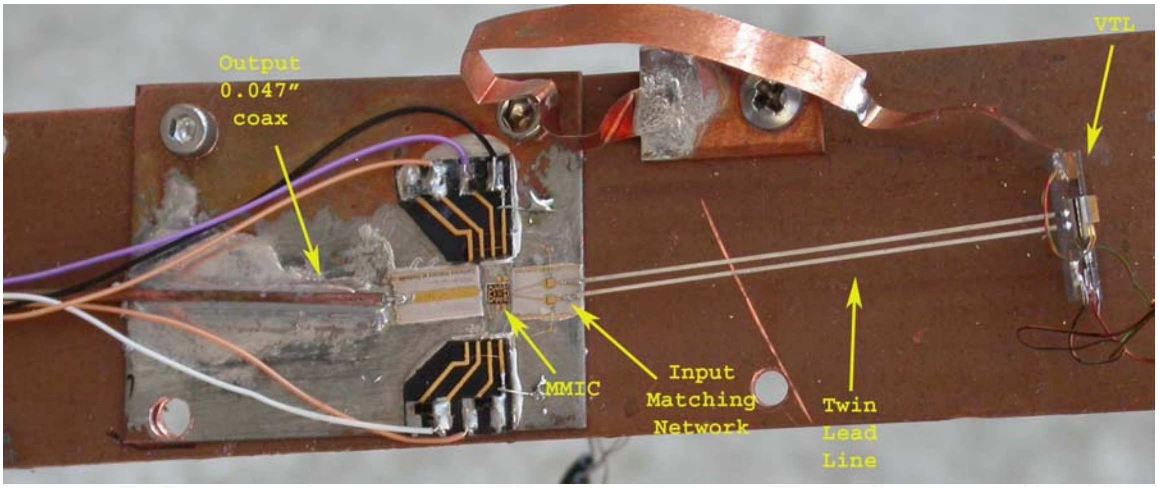

Fig 7. Close-up of the active balun on a copper plate

3. Discussion

The room temperature measurements were done without the copper shield and with ground as far away as practically possible. As can be seen in Fig 4, there’s a large ripple in the noise of both the active and passive baluns. The period of 2.5 GHz for the active balun ripple, suggests a separation between two discontinuities of about 60 mm in air, which is approximately the distance between the 200 ohm source and the input of the MMIC. The 600 MHz period ripple of the passive balun is what we would expect if the reflections occurred at the 200 ohm resistor and the input of the LNA, under the condition that the signal travels in the twin lead line and then the intended way in the quartz substrate. The average effective dielectric constant of the balun is about 2.6 and the length about 125 mm. The cause of this ripple is unknown. Measurements of the return loss, looking into the balun’s unbalanced end with the 200 ohm VTL connected to the balanced side, show better than 15 dB across the entire band. This is with good agreement with simulations. The amplifiers should be very well matched on the input for frequencies higher than 4 GHz. If the ripple in noise was caused by a mismatch we would expect to see a large ripple in the gain as well. Figure 4 shows a very smooth gain curve, at least for the active balun.

One of the concerns with the passive balun is the possible excitation of even modes when located in a grounded enclosure [3]. This mode will be badly matched at the ends of the copper shield and will therefore form a resonant cavity. As can be seen in figure 5-6, sharp peaks in noise appear on top of the ripple we saw in the room temperature measurements. The peaks appear at the same frequencies with and without the shield, but they are sharper and larger in magnitude with the shield. Without the shield, the balun will still be enclosed in a grounded cavity, but the distance to the top cover of the 90 K shield is about 100 mm compared to about 10 mm with the copper shield on. It is also worth noting that the sharp peaks can not easily be distinguished in the gain curves, which suggests that a simple transmission measurement through a balun might not reveal the problem. The situation in the ATA dewar is quite different since the narrow end of the radiation shield is open which allows a possible even mode to radiate. The copper shield used in these measurements is closed in both ends and the even mode will be badly matched in both ends.

If the increase in measured noise caused by adding the balun between the LNA and the 200 ohm source, is considered to be of thermal nature, the loss of the balun can be calculated using Equation 1.

$$L_b = \frac{T_{tot} + T_b}{T_b + T_{LNA}}$$

Eq 1. Expression for balun loss, where L_b=loss of balun, T_{tot}= total measured noise temperature, T_b=physical temperature of balun, T_{LNA}=noise temperature of LNA

Figure 8 shows the result of Equation 1 applied to Figure 4-6. Since we have no noise measurements of the single-ended LNA except for at room temperature, the simulated noise of the LNA was used. The physical temperature of the balun was measured by gluing a Lakeshore silicon diode temperature sensor to the tip of the balun using cyanoacrylate. The temperature of the LNA side of the balun was measured by screwing a sensor to the LNA body. Cyanoacrylate has low thermal conductivity but also low viscosity, so a very thin layer can be applied and therefore the temperature gradient should be very small. The average balun temperature was used in Equation 1.
The loss of the balun at room temperature is mostly due to the finite conductivity of the conductor metal, and the loss of 1 dB at 11 GHz is close to what we would expect. At cryogenic temperatures the conductivity of the top gold layer should increase by a factor of about 8 at 77K and up to several thousand at 12 K and therefore we would expect a large decrease in balun loss. As can be seen in figure 8, the balun loss seems to be quite constant down to 77K and at lower temperatures it even increases. At low temperatures, especially below 70K, the conductivity of metals is very dependent on their purity. To check for this, the DC-resistance of the top trace of the balun was measured at 300K and with the balun immersed in liquid nitrogen. The result is presented in Table 2 together with a reference measurement of a 100 ohm line on Duroid 6002, with 17 µm copper and 5 µm electroplated gold.

	@300 K	@77 K	@12 K
Temperature of crystal quartz balun base	300 K	79.50 K	13.35 K
Temperature of crystal quartz balun tip	300 K	85.50 K	16.65 K
Temperature of fused quartz balun base	300 K	79.30 K	13.35 K
Temperature of fused quartz balun tip	300 K	120 K	69.50 K
Resistance of crystal quartz top trace	2.36 Ω	0.49 Ω	-
Resistance of fused quartz top trace	3.68 Ω	1.07 Ω	-
Resistance of a 100 ohm line on 20 mil Duroid 6002	44 mΩ	5.8 mΩ	-

Table 2. Measurement results of the two baluns related to thermal and electrical conductivity.

The metal stack-up of the crystal quartz balun starting from the bottom layer is 0.1µm Ti, 2.5 µm Cu, 1 µm Ni and 0.5 µm Au. The fused quartz balun has only Au on Ti of unknown thicknesses. The DC-measurement of the crystal quartz balun does not say much about its microwave loss, because of its multilayer structure. The fused quartz balun only has one layer of high conductivity metal and it should therefore be safe to say that the change in conductivity between 300 and 77K in Table 2 is in the gold layer. It drops with a factor of 3.4 which should be compared with the theoretical value of 8. This indicates that the gold is not of high purity. Processing the substrates at very high temperatures can make the underlying metal to diffuse into the gold. The gold on both baluns looks very shiny which is not typical for pure gold. The crystal quartz balun used in these experiments even has areas where the top metal is nickel colored. It is not likely that poor metallization alone explains the higher-than-expected-noise. This poses the question whether the measurements are correct or not. There's no easy way to check the accuracy of this completely new type of noise measurement system. The fact that the measurements of the active balun is quite close to simulations is a strong indication that the noise measurement system is working and that it gives results that are close to the truth. Repeatability was very good and therefore the noise system should be an accurate tool to compare the different cases. Future measurements will give us more experience with the system and then we will be able to tell more about the absolute accuracy.

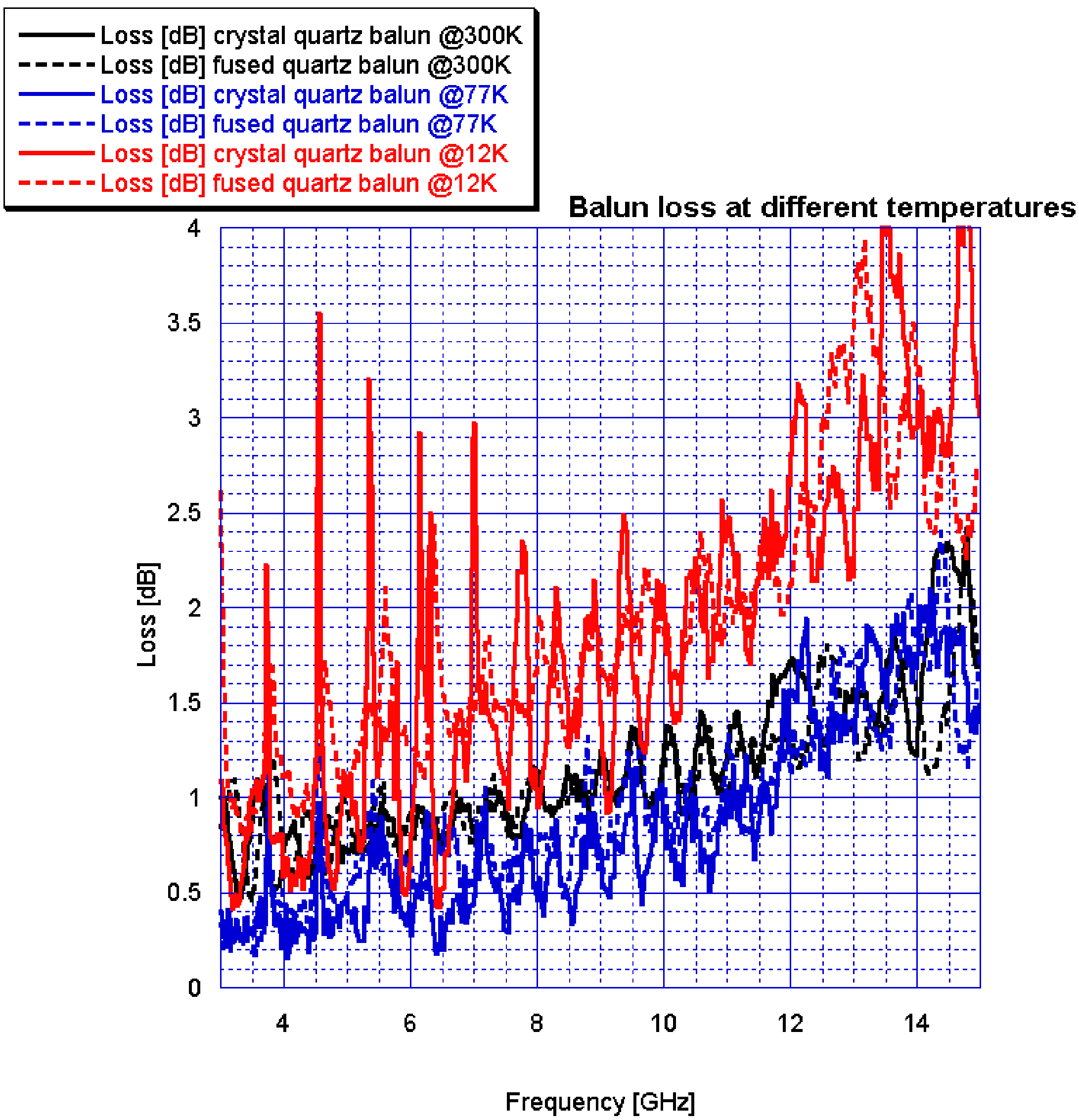

Fig 8. Calculated balun loss at different temperatures

4. Conclusions

The noise and gain of a crystal and a fused quartz balun connected to the single-ended ATA LNA (WBA13) was measured at 300, 77 and 12 K physical temperature, using a new type of differential noise measurement system. The measured noise at 300K agrees well with simulations, but at 77 and 12K it is considerably higher than expected. The reason for this seems to be excessive loss in the baluns, and in the fused quartz case, also the fact that it does not cool down all the way to the tip. DC measurements of the top trace resistance indicate that the excessive balun loss can partly be explained by an impure gold top layer.
Measurements at room temperature show a large periodic ripple in the noise. The period of 600 MHz suggests discontinuities at the LNA and the 200 ohm source, and a signal traveling through the twin lead line and then the intended way through the quartz substrate. The reason for this ripple is unknown.

With the copper foil shield around the balun, sharp peaks appear in the noise at certain frequencies. Also without the shield these peaks appear when the baluns are located inside the 12 or 77K dewar. The reason for these peaks is even mode excitation and is discussed in [3]. It is suggested that the measurements in this report are repeated with a conical ATA shield around the balun to check if the peaks remain or not.

The measurements of the active balun show pretty good agreement with simulations at all three temperatures. The noise has the same ripple as with the passive baluns, suggesting standing waves between the LNA and the 200 ohm source. The reason for this ripple needs to be investigated. The active balun also needs a proper module to make it less sensitive to unwanted feedback when placed in a metal enclosure, and for possible future testing in an ATA feed.

References:

[1] G. Engargiola, "*Tapered Microstrip Balun for ATA Feed Development", ATA memo 35*
[2] G. Engargiola , *"Tapered microstrip balun for integrating a low noise amplifier with a nonplanar log periodic antenna",* Review of Scientific Instrument, VOLUME 74, NUMBER 12, December 2003
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