The Challenges of Extending the IF Bandwidth of ALMA Band 6 SIS Mixer-Preamps to 12 GHz and 16 GHz with Optimal Noise Performance: An Experimental Demonstration

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I. Introduction

This proposal had two main developmental goals. First was to develop three broadband IF amplifiers covering 4-12 GHz, 4-16 GHz and 4-20 GHz using commercially available devices from Diramics, a Swiss company, that could be integrated with the existing designs of Band 6 SIS mixers. The noise performance of the Diramics devices equals, on the average, the best ever demonstrated in any technology and is considered approaching the natural limit of noise performance of InP HEMTs [1]. The measured and modeled results of those three IF amplifiers are summarized in Section II. The second goal was to study an integration of these amplifiers with Band 6 SIS mixers [2]. The noise temperature T_R of cascade of an SIS mixer followed by an IF amplifier is given by:

$$T_R = T_M + L_M^{Av} T_A^{Y_M} \quad , \tag{1}$$

where T_M is the mixer noise temperature, L_M^{Av} is the mixer available conversion loss and $T_A^{Y_M}$ is the IF amplifier noise temperature while driven by the output admittance Y_M of the SIS mixer. Consequently, for proper accounting of different noise contributions to the receiver noise temperature T_R , the four noise parameters of the IF amplifiers need to be known in addition to the available conversion loss L_M^{Av} and the output admittance Y_M of the SIS mixer.

The interaction of the broadband IF amplifiers with SIS mixers would produce noise patterns at IF from which the parameters of SIS mixer T_M , L_M^{Av} and Y_M could be deduced. Therefore, in the first set of experiments, the test SIS mixers were directly connected to IF amplifiers through a 50 Ω line. The results of these experiments and their interpretation by a simple model for a test SIS mixer and three IF amplifiers having different instantaneous bandwidths are described in Section III.

The results of early experiments described in [3] indicated that 100 Ω in parallel with 0.3 pF could approximate output admittance of the pumped Band 6 SIS mixer. The test and modeling results of Section III confirmed these estimates. These findings, however, are in a disagreement with the theoretical prediction from the generally accepted SIS mixer model. Consequently, Section IV further explores this issue.

A use of a cryogenic isolator inserted between an SIS mixer and an IF amplifier breaks a direct noise interaction between these two components. In addition, the noise parameters of a cascade of isolator and IF amplifier can be easily predicted [4],[5]. Furthermore, the 4-12 GHz isolator from Low Noise Factory [6] could be used in a circulator mode, allowing for an injection of the calibrated noise toward the output of SIS mixer, and in turn allowing for the measurement of the magnitude of SIS mixer output admittance $|Y_M|$. The results of experiments using Band 6 SIS mixer, 4-12 GHz Low Noise Factory isolator/circulator and 4-12 GHz IF amplifier and their interpretation by a simple model are described in Section IV.

The knowledge of the mixer available conversion loss L_M^{Av} and its output admittance Y_M and the knowledge of signal and noise parameters of the IF amplifiers allow for a design of noise matching network between SIS mixer and IF amplifiers which could be considered optimal from the point of view of noise performance averaged over the IF bandwidths. Consequently, it allows for the accurate estimation of noise penalties resulting from extending IF bandwidths of SIS mixer-IF amplifier cascade. The noise optimal integration of Band 6 mixer with IF amplifiers are discussed in Section V.

Finally, a discussion of results and conclusions are offered in Section VI.

II. IF Amplifiers

Early in 2021, a good model of the Diramics 200 micron wide devices was developed and three different amplifiers, 4-12 GHz, 4-16 GHz, and 4-20 GHz were designed. The expected noise and gain performance of these three designs are shown in Fig. 1. The designs had the same form factor as the existing Band 6 4-12 GHz IF amplifier, although the internal structure and the substrates used were different. The design data of Fig. 1 illustrate a very important point that extending the IF bandwidth by increasing the higher frequency of the IF band will always result in a penalty to average noise across the IF band.

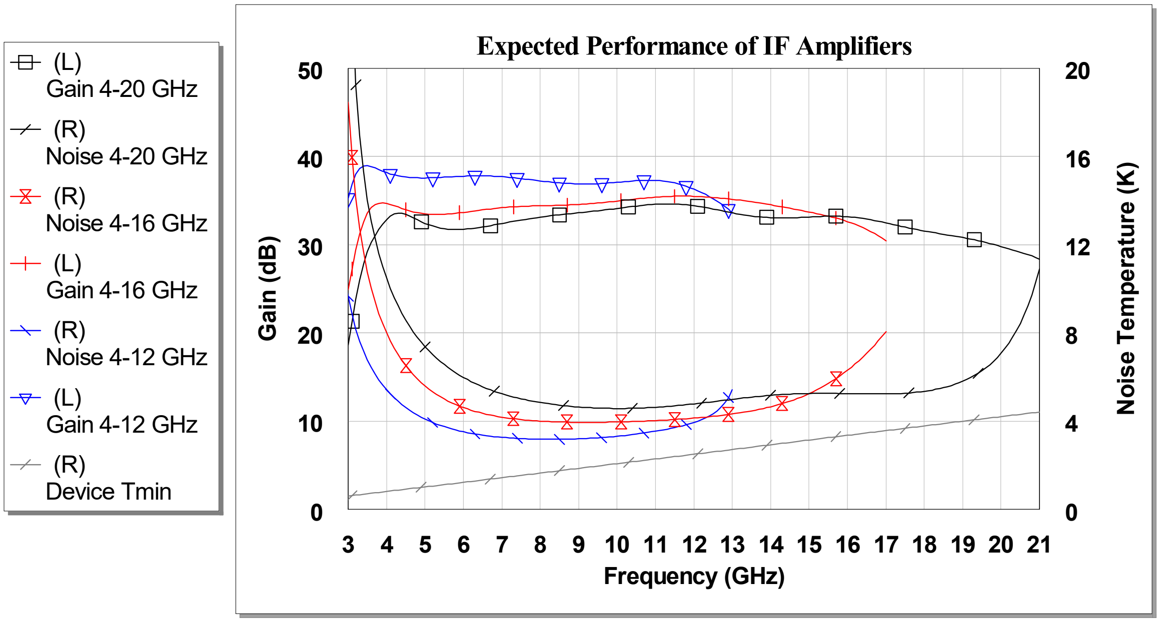


Fig. 1. Expected noise and gain performance of 4-12 GHz, 4-16 GHz and 4-20 GHz IF amplifiers at 15 K ambient temperature. For comparison the minimum noise temperature of Diramic' HEMT at 15 K ambient is also plotted.

Unfortunately, it soon became clear that there were significant barriers to the practical realization of these designs. The main one was that a trusted supplier of Cuflon substrates and their processing, Polyflon Company [7], declined our RFQ, deeming it too small. The search for other reliable providers was marred by their lack of experience processing Cuflon substrates. That left us with two options: either to redesign using Duroid substrates or build the test amplifiers using the existing amplifier bodies and “handmade” substrates out of the array of substrates we had available for many other NRAO amplifier designs. The other supply chain issues, Covid-19 work restrictions and the demand on tech–specs’ time by other important NRAO projects, directed us to follow the second route.

The designs of amplifiers that were built and tested, given the above-mentioned restrictions, were slightly less than optimal from the noise temperature point of view. Nevertheless, these designs were entirely sufficient to test the agreement between model derived and experimental results and, therefore, to assess penalties in noise performance related to broadbanding of IF amplifiers. The modeled and measured performance of IF amplifiers are shown in Figs. 2 and 3 for 4-12 GHz amplifier, Figs. 4 and 5 for 4-16 GHz amplifier and Figs. 5 and 6 for 4-20 GHz amplifier. For completeness, a comparison of measured noise and gain performance of 4-12 GHz, 4-16 GHz and 4-20 GHz IF amplifiers at 15 K ambient temperature is shown in Fig. 8.

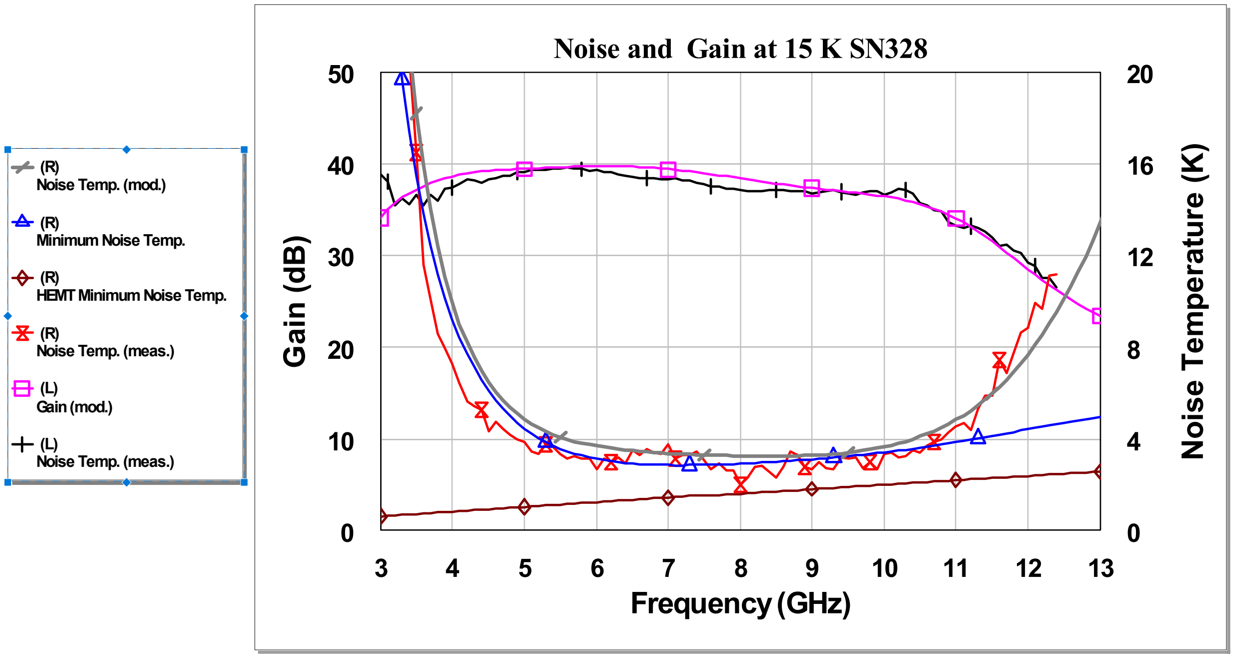


Fig. 2. Modeled and measured noise and gain performance of 4-12 GHz amplifiers at 15 K ambient temperature. For comparison, the modeled minimum noise temperature of the Diramics InP HEMT at 15 K ambient (brown) and the minimum noise temperature of the amplifier (blue) are also plotted.

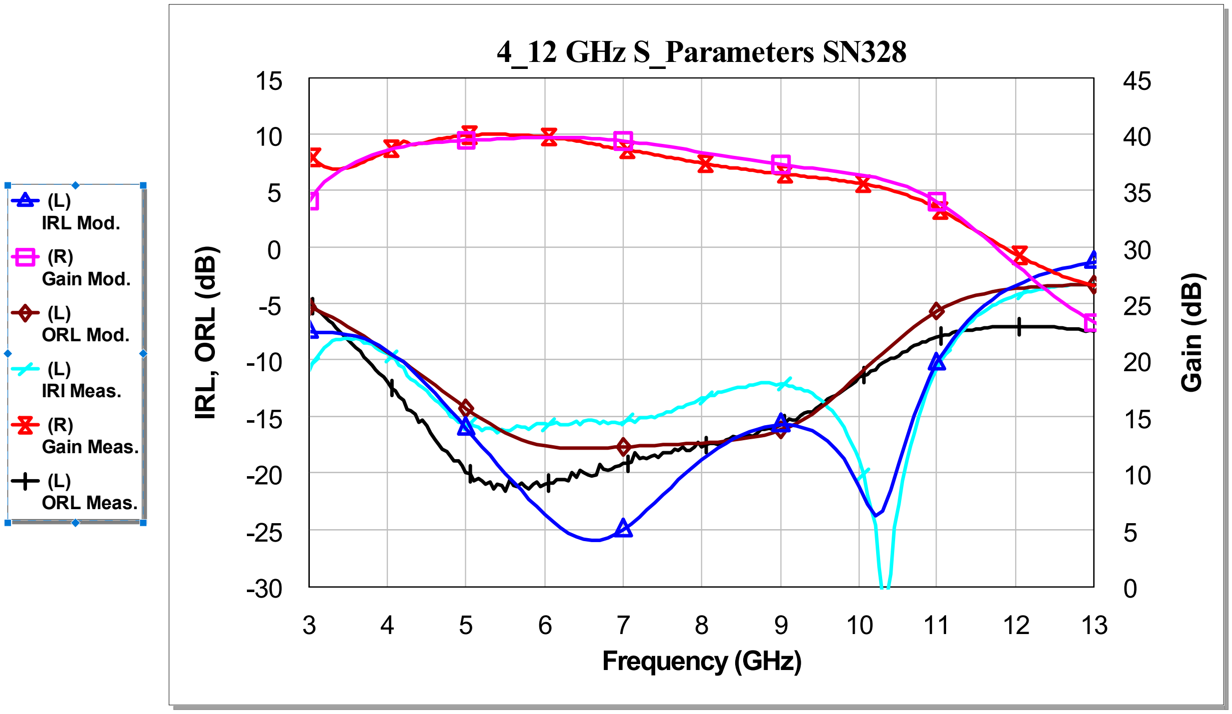


Fig. 3. Modeled and measured S-parameters 4-12 GHz amplifier at 297 K ambient temperature.

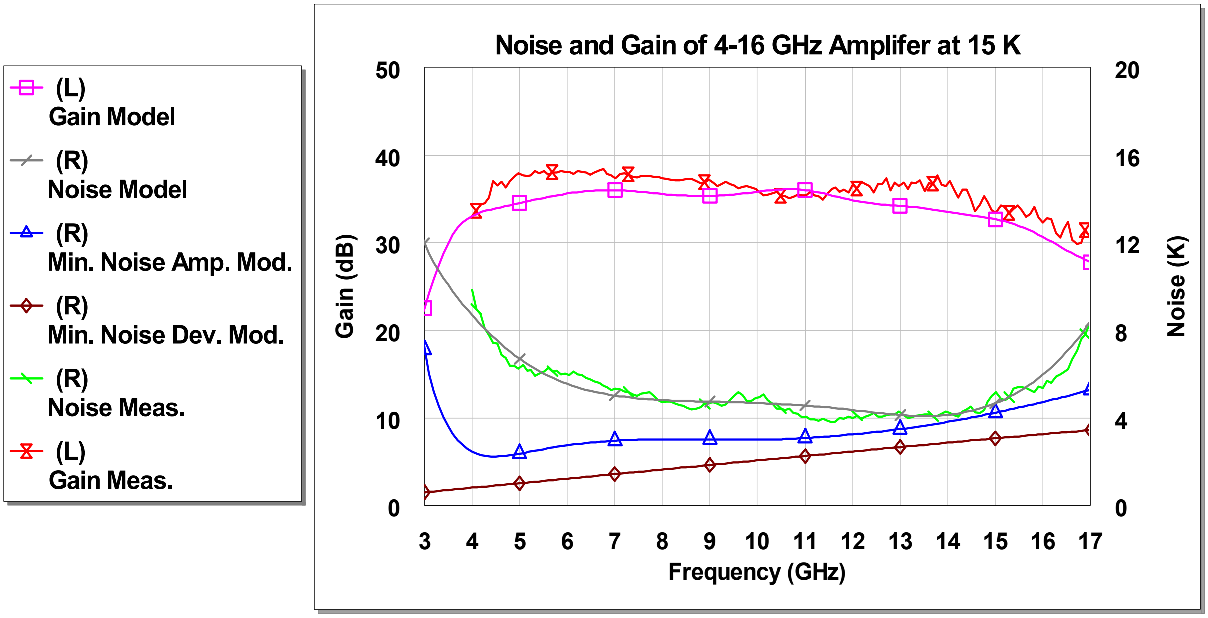


Fig. 4. Modeled and measured noise and gain performance of 4-16 GHz amplifier at 15 K ambient temperature. For comparison, the modeled minimum noise temperature of the Diramics InP HEMT at 15 K ambient (brown) and the minimum noise temperature of the amplifier (blue) are also plotted.

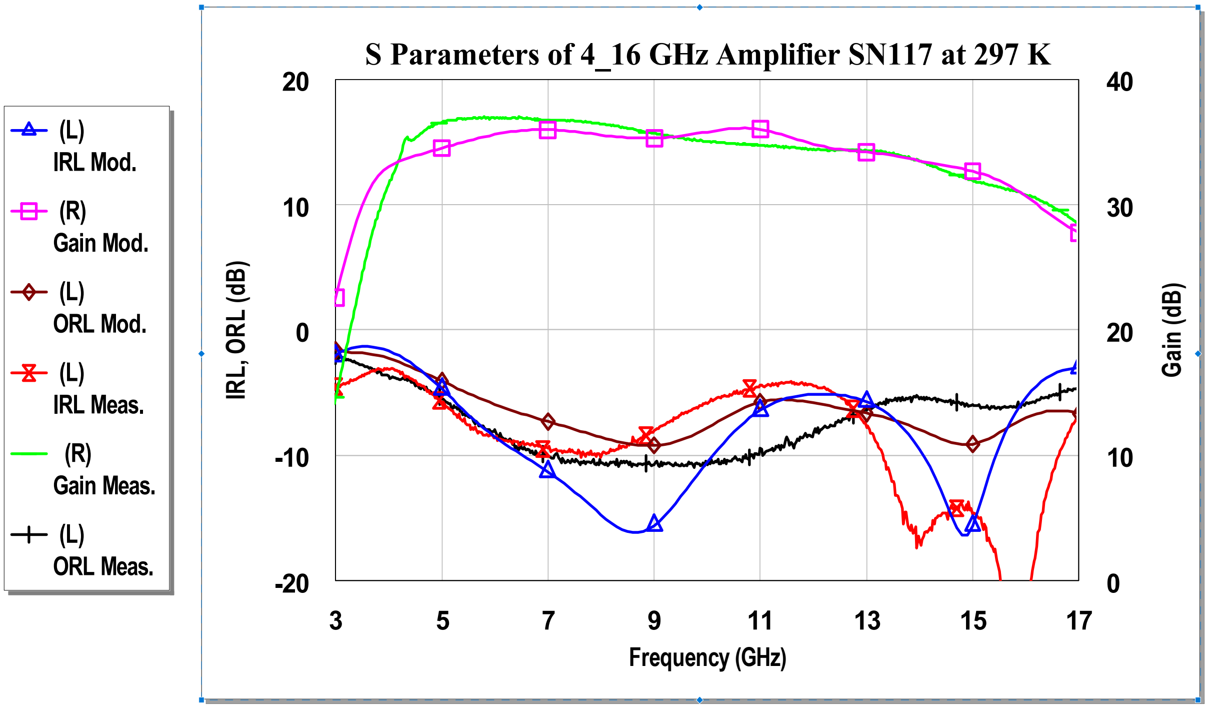


Fig. 5. Modeled and measured S-parameters 4-16 GHz amplifier at 297 K ambient temperature.

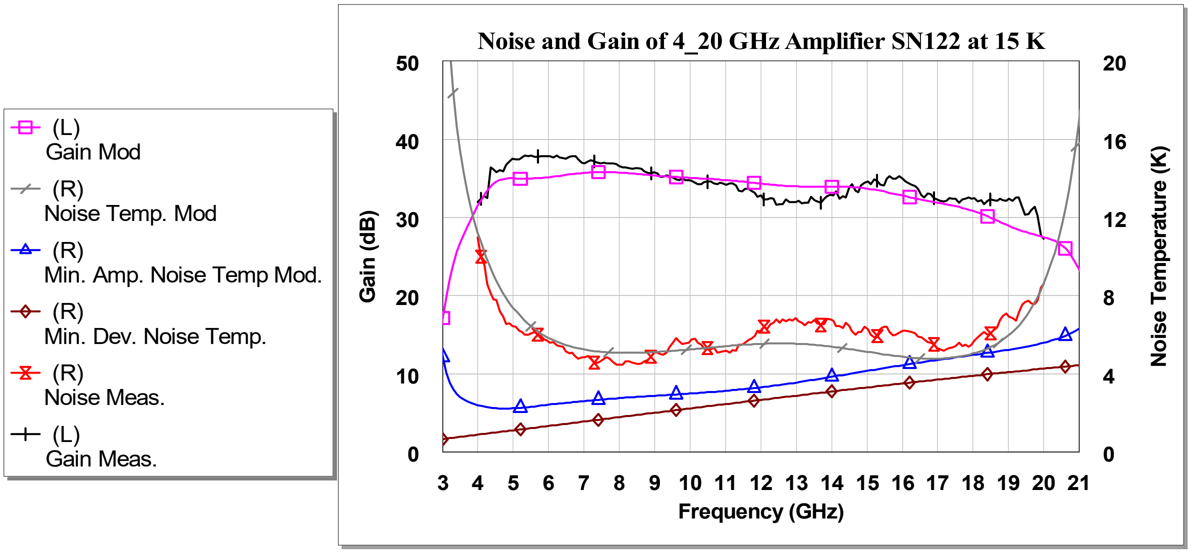


Fig. 6. Modeled and measured noise and gain performance of 4-20 GHz amplifier at 15 K ambient temperature. For comparison, the modeled minimum noise temperature of the Diramics InP HEMT at 15 K ambient (brown) and the minimum noise temperature of the amplifier (blue) are also plotted.

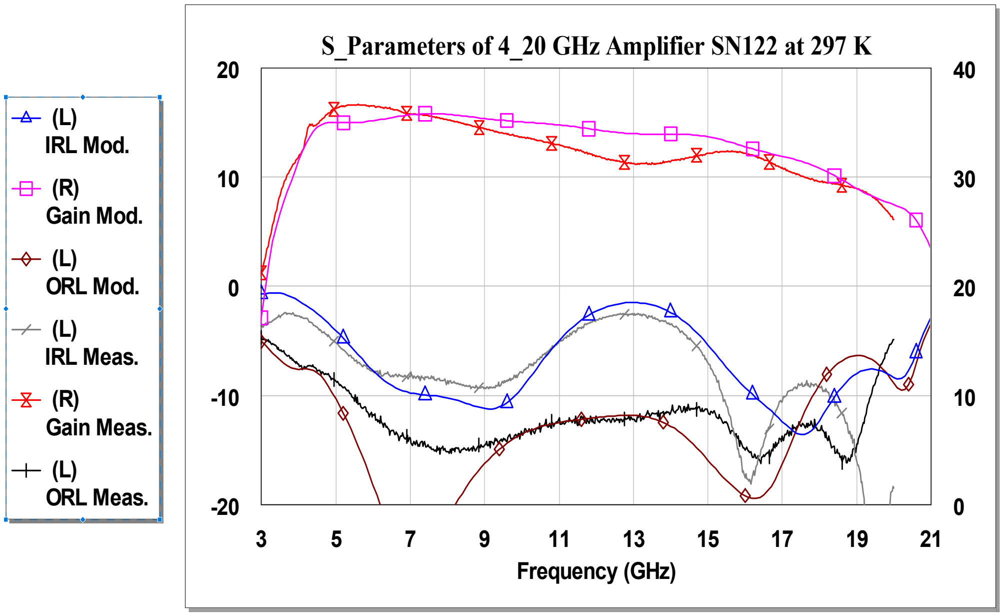


Fig. 7. Modeled and measured S-parameters 4-20 GHz amplifier at 297 K ambient temperature.

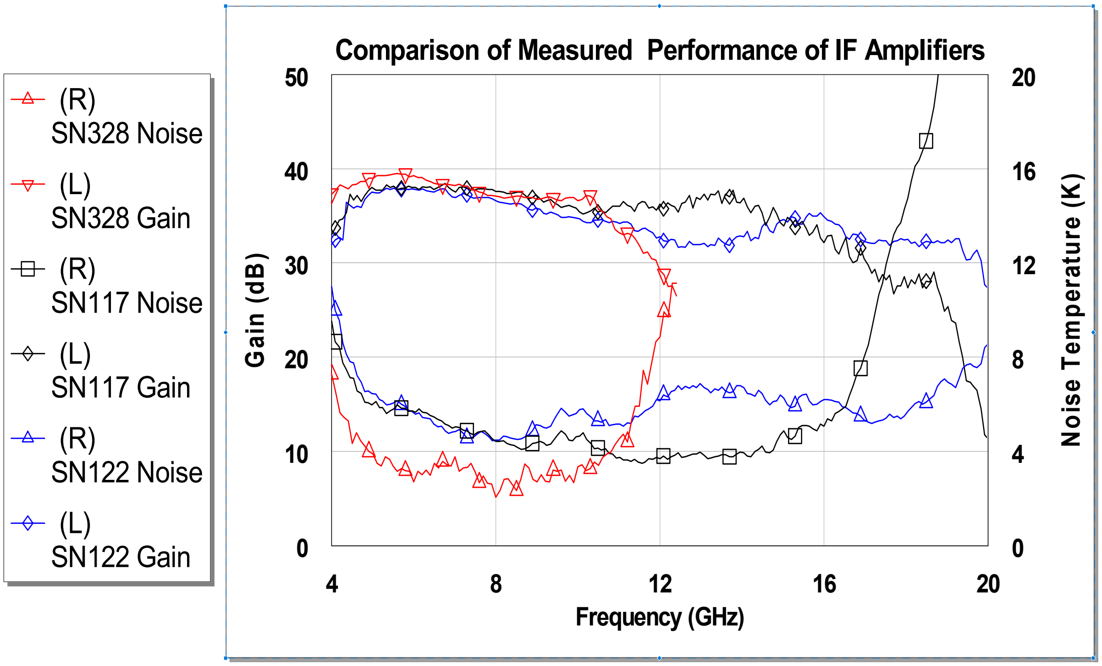


Fig. 8. Comparison of measured noise and gain performance of realized 4-12 GHz, 4-16 GHz and 4-20 GHz IF amplifiers at 15 K ambient temperature.

III. Tests with SIS Mixer Directly Connected to IF Amplifiers Through a 50 Ω Line

The schematic of dewar configuration for the measurement of SIS mixer/IF amplifier tandems connected through 50 Ω line is shown in Fig. 9. The SIS tests fixture described in [8],[9] was used. The photograph of the test fixture with cover removed and its Microwave Office equivalent circuit is shown in Fig. 10. The coaxial output of the test mixer mount was connected through an adapter to coaxial inputs of IF amplifiers. The effective electrical length of this connection was not known and therefore the length of this coaxial line was marked as adjustable in the Microwave Office schematic.

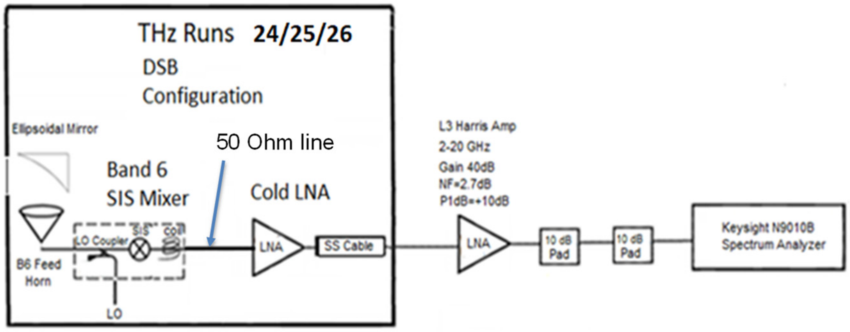


Fig. 9. Schematic of dewar configuration for the measurement of a cascade SIS mixer and IF amplifier connected through 50 Ω line.

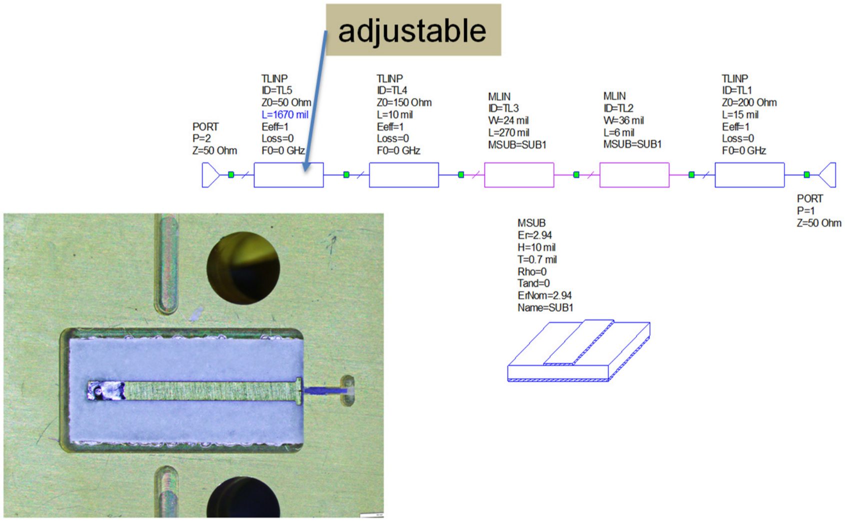


Fig 10. Photo of the test SIS mixer mount [8], [9] with the cover removed and Microwave Office schematic of the circuit connecting SIS mixer (Port 1) with IF amplifiers (Port 2). The adjustable 50 Ω line in the schematic represents coaxial connectors between the output of test mixer mount and the inputs of IF amplifiers which effective length was not known a priori.

The typical I-V characteristics of the un-pumped and pumped SIS test mixer were excellent with always-positive dynamic resistance for any local oscillator frequency. Typical characteristics for LO frequency of 245 GHz is shown in Fig 11. The plots of measured DSB noise performance of the test mixer connected to the 4-12 GHz amplifier of Figs. 2 and 3 for all local oscillator frequencies are shown in Fig. 12.

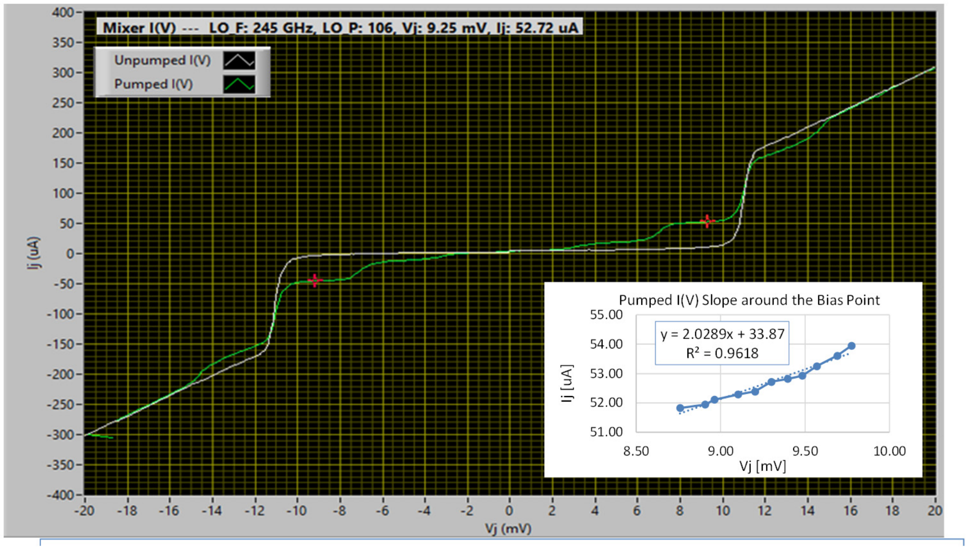


Fig. 11. The example of Band 6 SIS I-V characteristics, un-pumped and pumped at LO frequency of 245 GHz.

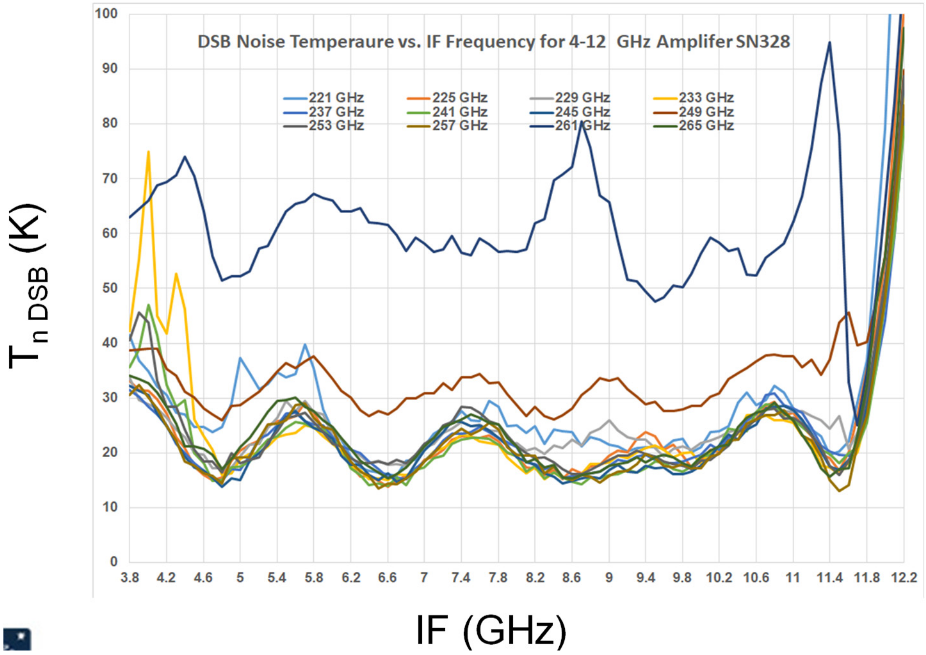


Fig 12. Measured DSB noise temperatures of SIS/4-12 GHz amplifier tandem versus IF for all local oscillator frequencies covering ALMA Band 6.

The measured data of Fig. 12 lead to several very important observations. There are noise patterns with minima and maxima spaced uniformly across the IF band illustrating the fact that at some IFs, the output admittance of the pumped SIS mixer is well noise matched to the IF amplifier and at other frequencies, it is quite mismatched. The number of these minima and maxima is dependent on the electrical length of the 50 Ω connection between the SIS mixer chip and the IF amplifier. At IFs at which there exist a good noise match the performance of this SIS/IF amplifier tandem is truly exceptional as the minima hover around 15 K DSB. The IF noise pattern is very repeatable for the whole Band 6 range of the LO frequencies. This last observation might not seem obvious unless the noise traces for some LO frequencies are removed from Fig. 12 plots as it is shown in Fig. 13. It is important to note, that the data for this limited set of LO frequencies shown in Fig. 13, still covers in a DSB mode all frequencies in ALMA Band 6. Consequently, the unrepeatability of noise traces as some LO frequencies included in Fig. 13 can only be attributed either to the insufficient LO power or to the LO added noise. The remarkable repeatability of IF noise plots shown in Fig. 13 implies that for Band 6 mixer design the IF output admittance is practically independent of LO frequency.

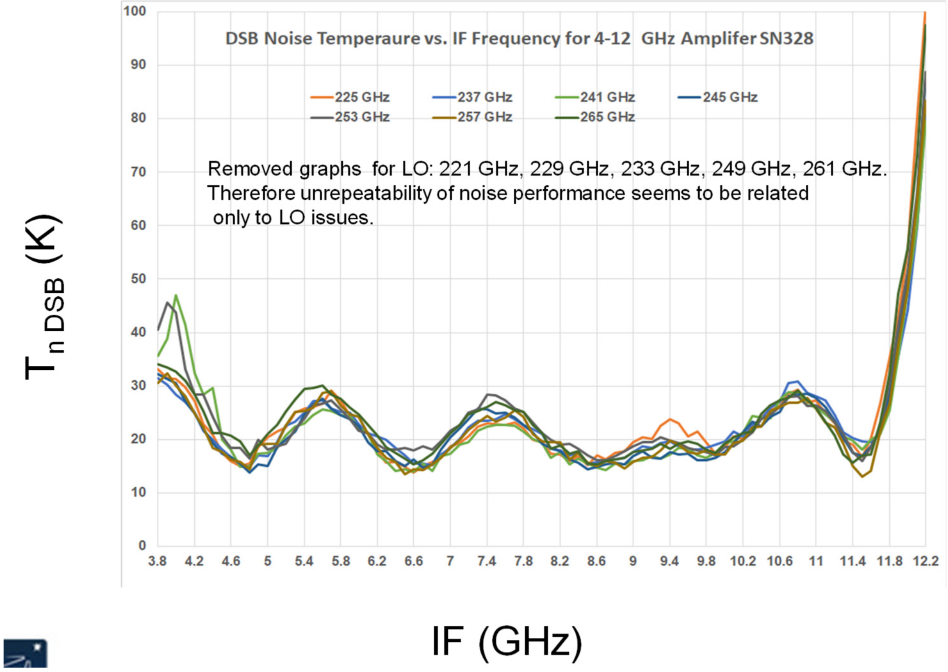


Fig 13. Measured DSB noise temperatures of SIS/4-12 GHz amplifier tandem versus IF frequency for a limited set of local oscillator frequencies, but still covering fully ALMA Band 6.

Referring to equation (1), the plots of DSB receiver noise temperatures of Fig. 13 allow inferring some mixer parameters, that is the mixer noise temperature T_M, the mixer available conversion loss L_M^{Av} and the output admittance Y_M of the pumped SIS mixer. The values of Y_M and L_M^{Av} for Band 6 mixer were already estimated from the initial experiments described in the proposal [3] for this follow-up study. These early experiments indicated that 100 Ω in parallel with 0.3 pF could approximate output admittance Y_M of the pumped Band 6 SIS mixer and available SSB conversion loss L_M^{Av} could be estimated at 7 dB. Using these values and the models of 4-12 GHz amplifier and connecting circuit (Fig. 10) one could compare the measured IF noise patterns with those predicted from equation (1). This comparison for LO frequency of 245 GHz is shown in Fig. 14. In this case, the SSB noise temperature was assumed twice the measured DSB noise temperature presented in Fig. 13. This experiment and subsequent modeling were repeated using the same test SIS mixer and 4-16 GHz and 4-20 GHz IF amplifiers. The comparison of modeled and measured results is shown in Figs 15 and 16, respectively. The models of amplifiers described in Section II were used. For all three examples, the only change to the circuit model was an adjustment of the electrical length of the 50 Ω line as indicated in the schematic in Fig. 10. In all three cases, the mixer noise temperature $T_M = 16\ K$ was assumed. It accounts not only for SIS mixer noise temperature but also for all other noise contributions of preceding elements, including LO injection coupler, dewar optics and dewar window.

The agreement between measured and modeled results is very good for all three examples with the exception of 15 -20 GHz frequency range. Two possible explanations were considered. The first was the existence of higher order modes in the test mixer housing. It has been ruled out by both calculation and measurement. The second and the most probable was that the right-angle transition (see Fig. 9) between microstrip and coaxial 3.5 mm connector could not be modelled as perfect 50 Ω line in this frequency range.

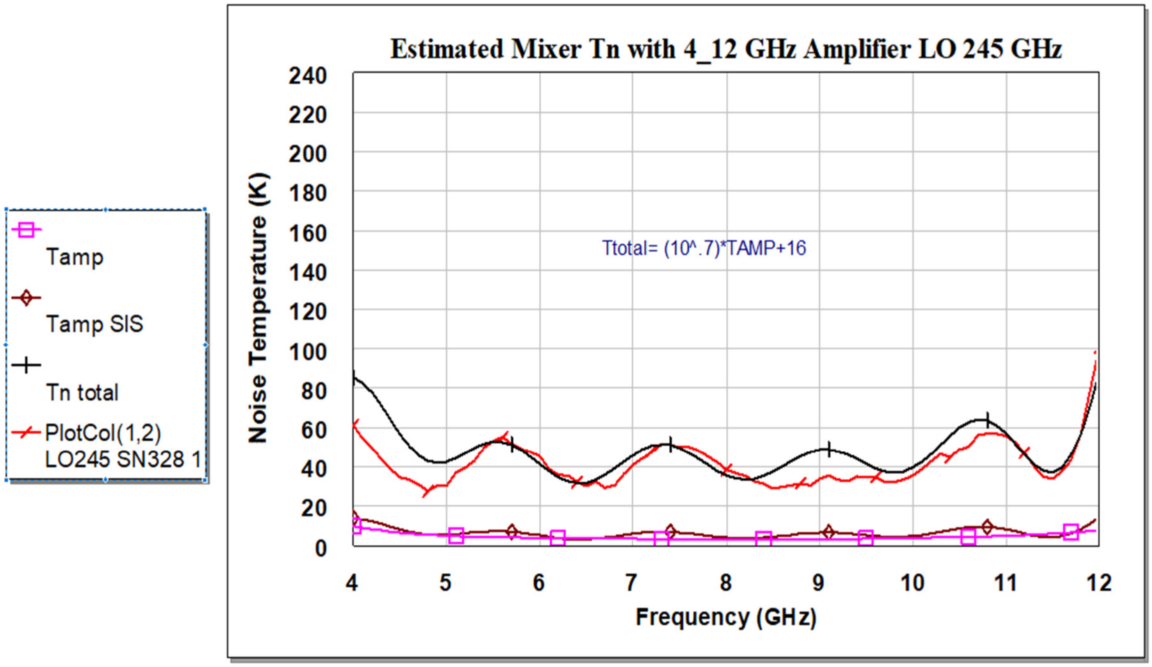


Fig 14. Measured (red) and modeled (black) SSB noise temperatures of SIS/4-12 GHz amplifier tandem versus IF frequency for LO frequency of 245 GHz. The noise temperatures of IF amplifier as driven by 50 Ω generator (magenta) and as driven by output admittance Y_M of SIS mixer (brown) is also shown. $T_M = 16\ K$ was assumed.

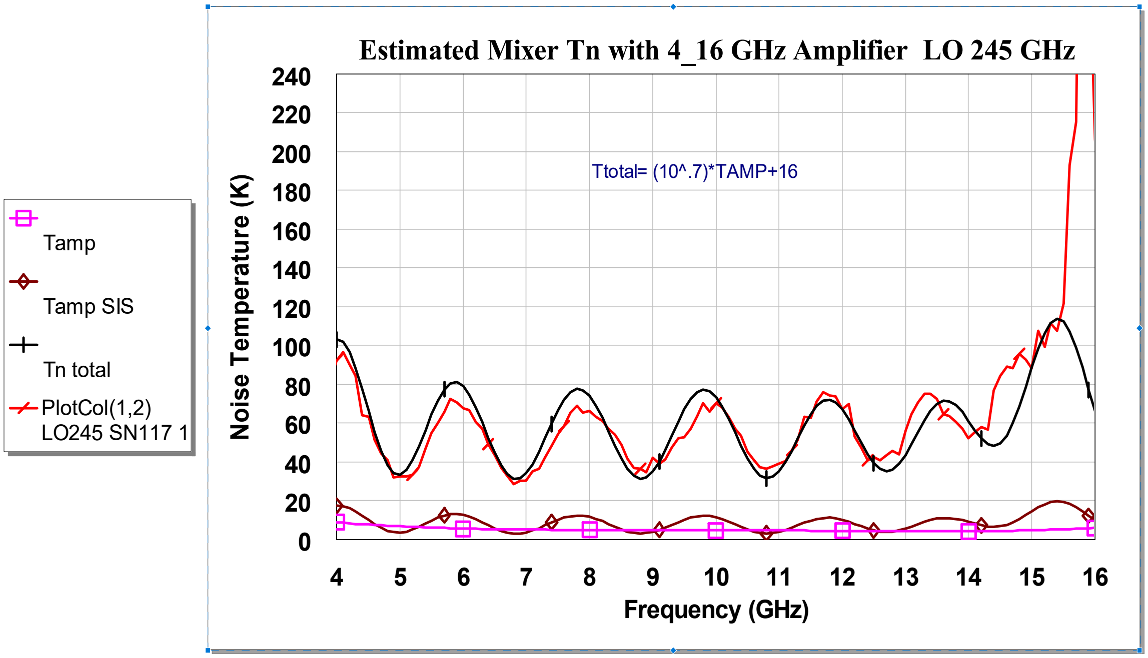


Fig 15. Measured (red) and modeled (black) SSB noise temperatures of SIS/4-16 GHz amplifier tandem versus IF frequency for LO frequency of 245 GHz. The noise temperatures of IF amplifier as driven by 50 Ω generator (magenta) and as driven by output admittance Y_M of SIS mixer (brown) is also shown. $T_M = 16\ K$ was assumed.

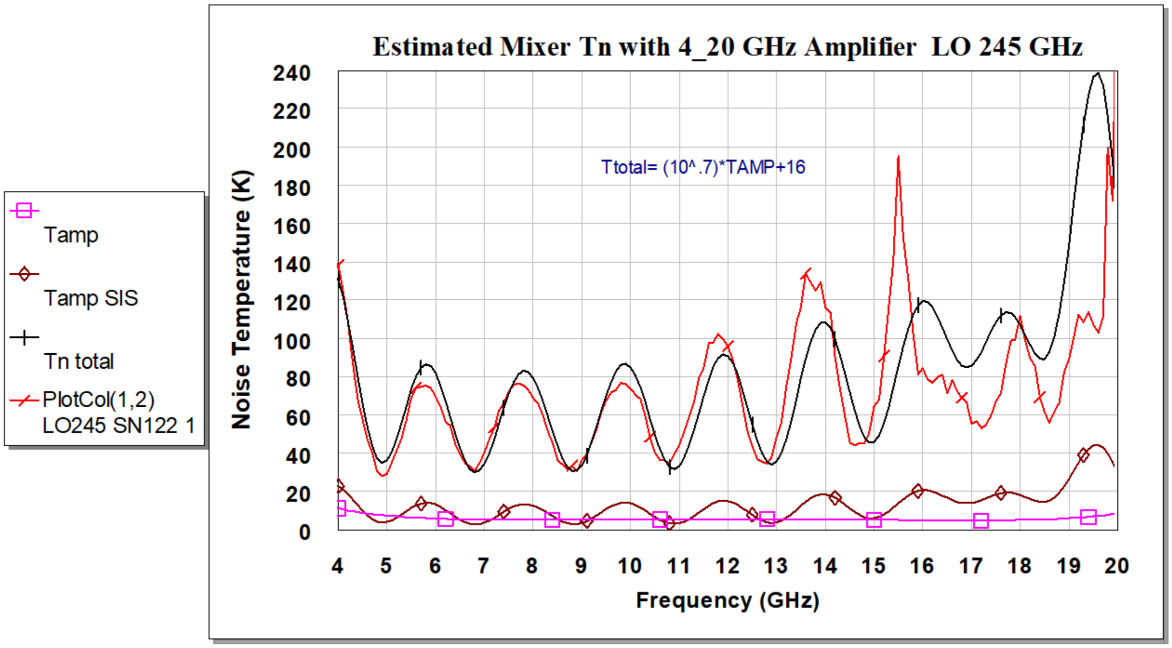


Fig 16. Measured (red) and modeled (black) SSB noise temperatures of SIS/4-20 GHz amplifier tandem versus IF frequency for LO frequency of 245 GHz. The noise temperatures of IF amplifier as driven by 50 Ω generator (magenta) and as driven by output admittance Y_M of SIS mixer (brown) is also shown. $T_M = 16\ K$ was assumed.

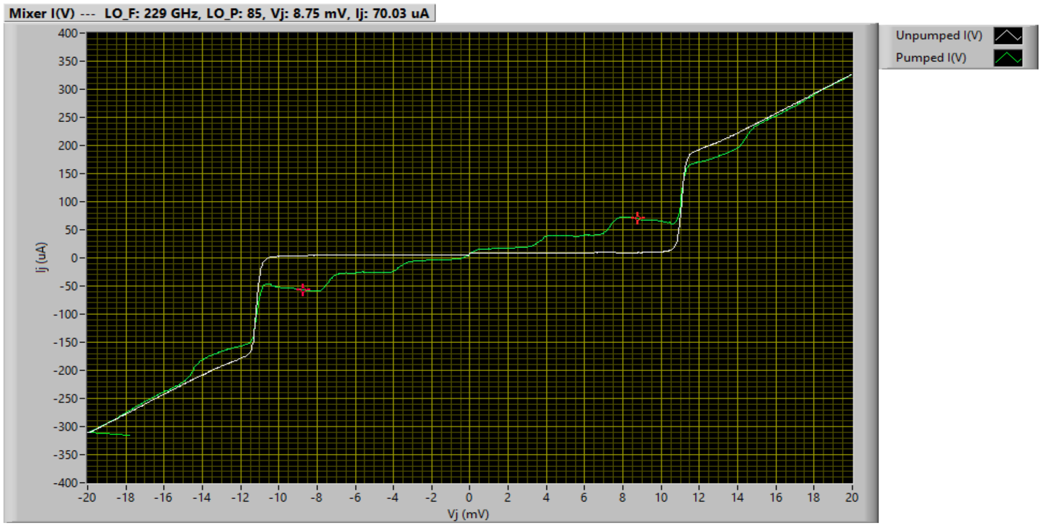
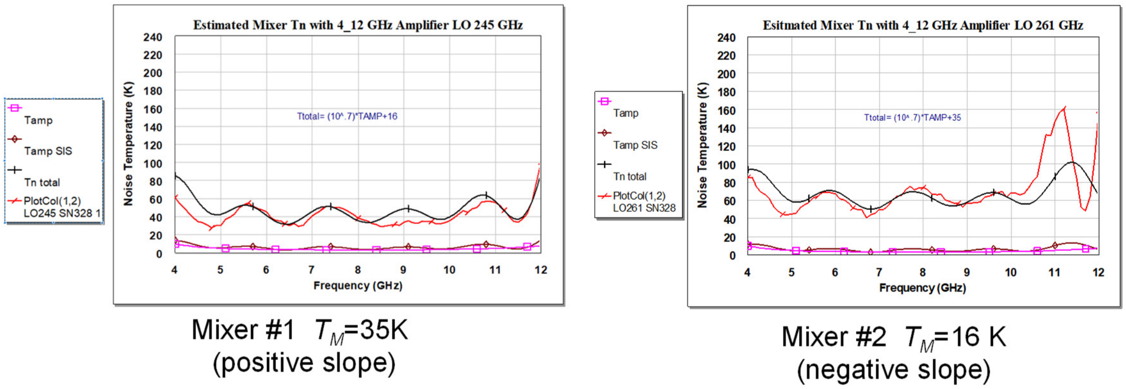


Fig. 17. The example of Band 6 SIS I-V characteristics, un-pumped and pumped demonstrating a negative dynamic resistance in the latter case (LO frequency of 229 GHz).



Mixer #1 T_M=35K (positive slope)

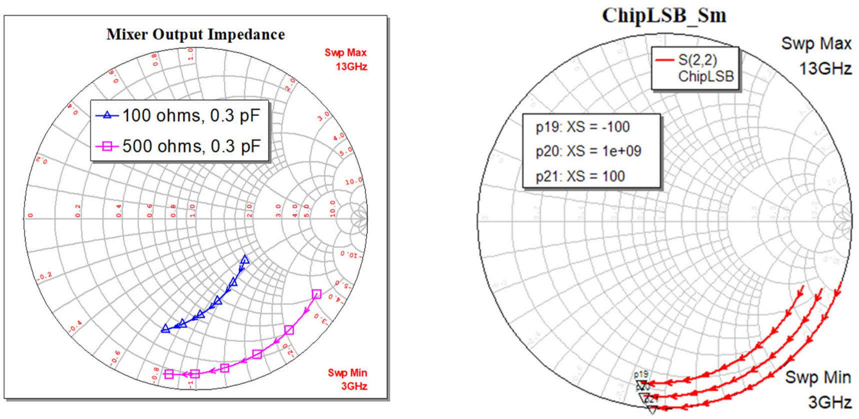
Mixer #2 T_M=16 K (negative slope)

Fig 18. Comparison of measured (red) and modeled (black) SSB noise temperatures of SIS/4-12 GHz amplifier tandems for two mixers: mixer #1 having the I-V characteristics shown in Fig. 11 and mixer #2 having I-V characteristics of Fig 17. Noise temperatures of IF amplifier as driven by 50 Ω generator (magenta) and as driven by output admittance Y_M of SIS mixer (brown) are also shown. For a good model $T_M = 35\ K$ was assumed for mixer #1 and $T_M = 16\ K$ was assumed for mixer #2.

Some of Band 6 mixers under pumped conditions are exhibiting negative dynamic resistance. The example of such characteristic is shown in Fig. 17. Red crosses indicate a typical dc bias point. This test mixer #2 mounted in the identical housing as shown in Fig. 10, was also tested for noise using the same, as in the case of test mixer #1, 4-12 GHz IF amplifier. A comparison of measured noise patterns for the two mixers, having I-V characteristics of Figs. 11 and 17, is shown in Fig. 18. The noise patterns are very similar and the only parameter of the model that needed adjustment was T_M which was changed from 16 K to 35 K. No adjustment to the values of output admittance Y_M of the pumped SIS mixer was needed to explain the IF noise pattern. Of note is a very large difference in demonstrated noise temperatures. It appears, it is only a property of the SIS mixer and therefore coincident with the existence of negative dynamic resistance (Fig.17). It was experimentally demonstrated that the mixers with negative dynamic resistance under pumped conditions might exhibit parasitic oscillations at frequencies below IF band. These parasitic oscillations can be tamed by frequency selective lossy circuit placed between the IF amplifier and SIS mixer [10]. Therefore, the cause of parasitic oscillations must be a negative output conductance of pumped SIS mixer, occurring only below the IF band. These findings, however, add only to the mystery of behavior of the output admittance Y_M of a pumped SIS mixer, as experimentally inferred Y_M values in 4-20 GHz IF range are in a disagreement with the theoretical prediction [2],[9]. Additional experiments addressing this problem and their interpretation are described in Section IV.

IV. Independent Estimation of Mixer Output Admittance and Conversion Loss

The simple “black box” model of Band 6 SIS mixer of Section III consistently explains the experimental results described in that Section for all three IF amplifiers. It explains correctly the measured noise IF noise patterns for a mixer followed by very different IF amplifiers. As already demonstrated in the proposal to this study [3], this simple model also correctly predicts the changes in IF noise pattern resulting from changes in the circuit between the SIS mixer and IF amplifier. Consequently, a large disagreement between the output conductance of pumped SIS mixer inferred from the experiments described in Section III and predicted from generally accepted SIS mixer theory [2], [9] is troubling. The scale of a problem is illustrated in Fig. 19, presenting plots of output admittance inferred from experiments and model predicted.

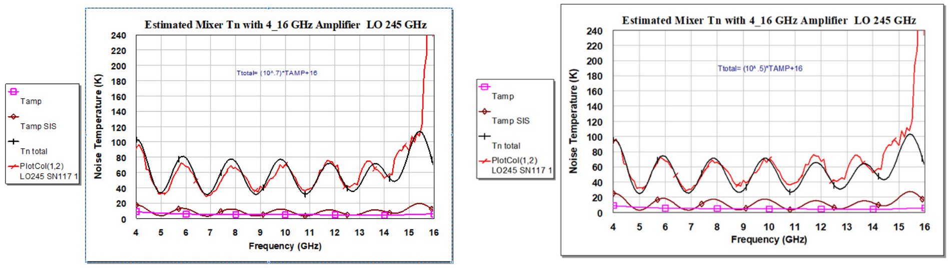


Inferred from noise patterns (blue)

Predicted from SIS mixer theory

Fig. 19. Plots of pumped Band 6 SIS mixer output impedance at IF frequencies. In blue, a parallel connection of 100 Ω and 0.3 pF, inferred from measured noise patterns, is plotted. In magenta, a parallel connection of 500 Ω with 0.3 pF is plotted which compares well with some SIS theory predicted values plotted in red.

There is a very good agreement between the values of parallel capacitance inferred from noise patterns and those predicted from Band 6 SIS mixer theoretical model. There is however a large disagreement between similarly derived values of parallel resistance. In the “black box“ model of SIS/IF amplifier tandem introduced in Section III, similar noise patterns could be obtained by increasing the value of parallel resistance and reducing the value of available conversion loss. An example of this exercise is shown in Fig. 20, demonstrating that similar noise patterns could be derived for different combination of values of parallel resistance and SIS mixer conversion loss L_M^{Av}. However, reasonable values of Y_M and L_M^{Av} could not bridge the discrepancy noted in Fig. 19.



Mixer # 1, T_M=16 K
Z_m= 100Ω//0.3 pF, L_M^{Av}=- 7dB

Mixer # 1 T_M=16 K
Z_m= 150Ω//0.3 pF, L_M^{Av}=- 5dB

Fig 20. Measured (red) and modeled (black) SSB noise temperatures of SIS/4-16 GHz amplifier tandem versus IF frequency for LO frequency of 245 GHz. The noise temperatures of the IF amplifier as driven by a 50 Ω generator (magenta) and as driven by output admittance Y_M of SIS mixer (brown) for two different cases are also shown. $T_M = 16\ K$ was assumed.

Facing this large discrepancy, a noise-only method of estimating the magnitude of both output return loss (ORL) of the pumped SIS mixer and its conversion loss was conceived[1]. The schematic of the measurement set–up is shown in Fig. 21. An LNF 4-12 GHz circulator and a coaxial switch were inserted between the SIS mixer and IF amplifier. A large ENR noise diode was connected to the third port of LNF 4-12 GHz amplifier through the bandwidth definition filter, cold 20 dB attenuator and dc block. This arrangement allowed for the calibration of the noise diode injected noise toward SIS mixer output by changing the switch position between a short (a perfect reflection) and a matched load, and therefore allowed for the measurement of the ORL of SIS mixer. It also allowed for the noise and gain calibration of the IF chain by switching between the hot and cold matched loads. Consequently, an estimation of DSB conversion loss of SIS mixer could be made by switching in turn between hot and cold loads at mm-wave frequencies.

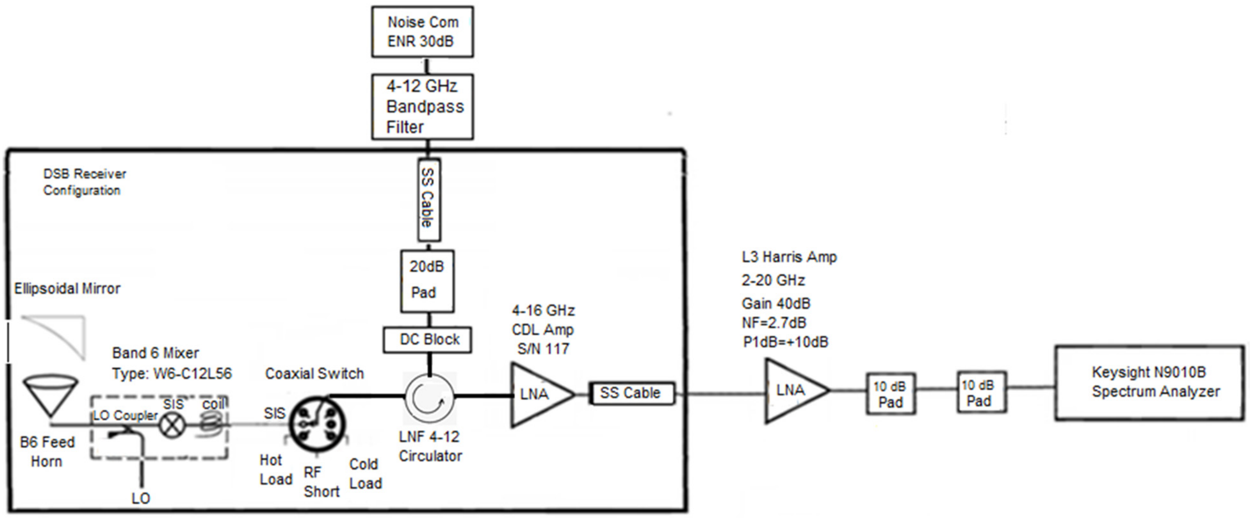


Fig. 21. Schematic of dewar configuration for the independent estimation of SIS mixer ORL and conversion loss

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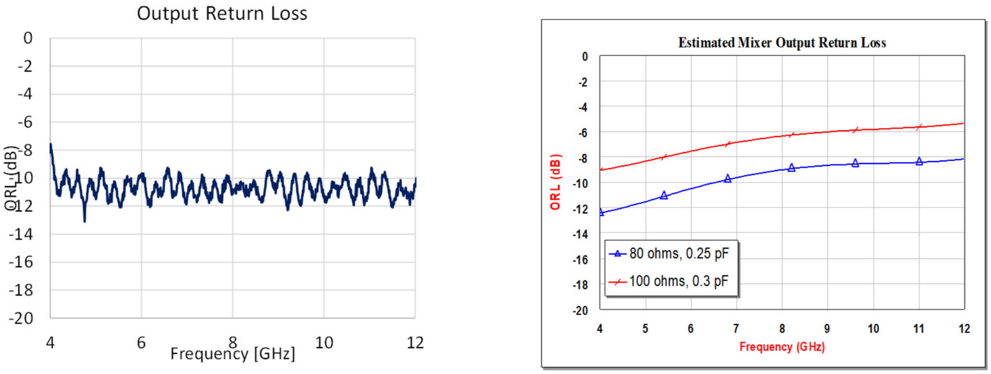
[1] Similar to the measurement setup used in [16]

The results of the noise based ORL measurement of pumped SIS mixer are compared in Fig. 22 with those predicted using two different set of values of resistance and capacitance modeling the output admittance Y_M. Similarly, the values of DSB conversion loss, measured with noise signal only, are shown in Fig. 23. The agreement between the parameters of the "black box" model of Section III and those estimated from noise only measurements in the system of Fig. 21 is not perfect. However, given relatively large errors of this method of measurement, the experimental data of Section III and Section IV should be considered consistent.



Measurement

Model

Fig. 22. Measured with noise only and modeled ORL of pumped Band 6 SIS mixer.

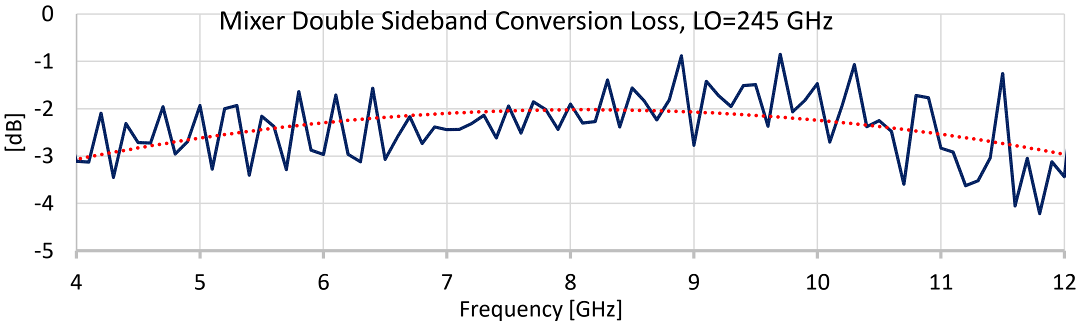


Fig. 23. Measured with noise only values of DSB mixer transducer conversion loss of pumped Band 6 SIS mixer.

V. Noise Optimal Integration of SIS Mixer with IF Amplifiers

A good understanding of Band 6 SIS mixer interaction with directly coupled IF amplifiers developed in Section III and IV allows for a design of optimal, with respect to average noise performance over a given IF band, SIS mixer–IF amplifier noise matching circuit. This experimental part of the study is still ongoing and the examples of optimal integration of 4-12 GHz, 4-16 GHz and 4-20 GHz IF amplifiers with Band 6 SIS mixers, are in development.

However, it is interesting to explore what determines the penalties in noise performance resulting from employing wider bandwidth IF amplifiers using examples of 4-12 GHz and 4-20 GHz amplifiers. The difference in average noise temperatures over the respective bandwidth of 4-12 GHz and 4-20 GHz amplifiers shown in Fig.1 is about 2.2 K. Similarly, the difference between the measured average noise temperature of 4-12 GHz and 4-20 GHz shown in Fig. 8 is also about 2.2 K. Given the transistors used perform close to the natural noise temperature limits [1], it would be safe to assume that this difference should approximately hold for any InP HEMT IF amplifier realization. Assuming 7 dB SSB available conversion loss L_M^{Av}, a simplistic approach would indicate that the lower bound on average noise penalty would be about 5 x 2.2 =11 K. However, the IF amplifiers of Fig.1 were designed to be noise matched to real source admittance of 50 Ω, while the output admittance Y_M of a pumped SIS mixer is complex. It cannot be made real, as every SIS mixer must possess RF choke presenting a virtual short to the RF signal, which at IF frequency can be approximated as parallel capacitance. This introduces additional noise penalties as it limits how well the IF amplifier can be noise matched to the output admittance Y_M . These noise penalties can only be explored in computer simulations. An example of what noise temperatures across IF band could be achieved if the mixer #1 of Section III were optimally integrated with 4-12 GHz amplifier is shown in Fig. 24.

For this numerical experiment, the design of a 4-12 GHz amplifier with expected performance as shown in Fig. 1 was used. For comparison, the modeled performance of the SIS mixer connected to 4-12 GHz through a coaxial connector from Fig. 14 was replotted (blue). These numerical experiments demonstrate that the average noise temperatures of about 35 K SSB for the best currently deployed Band 6 SIS mixers optimally integrated with 4-12 GHz amplifier are indeed possible. It also demonstrates that any attempt to connect directly an SIS mixer with IF amplifier through a 50 Ω connection of any length will result in an undesirable IF noise patterns.

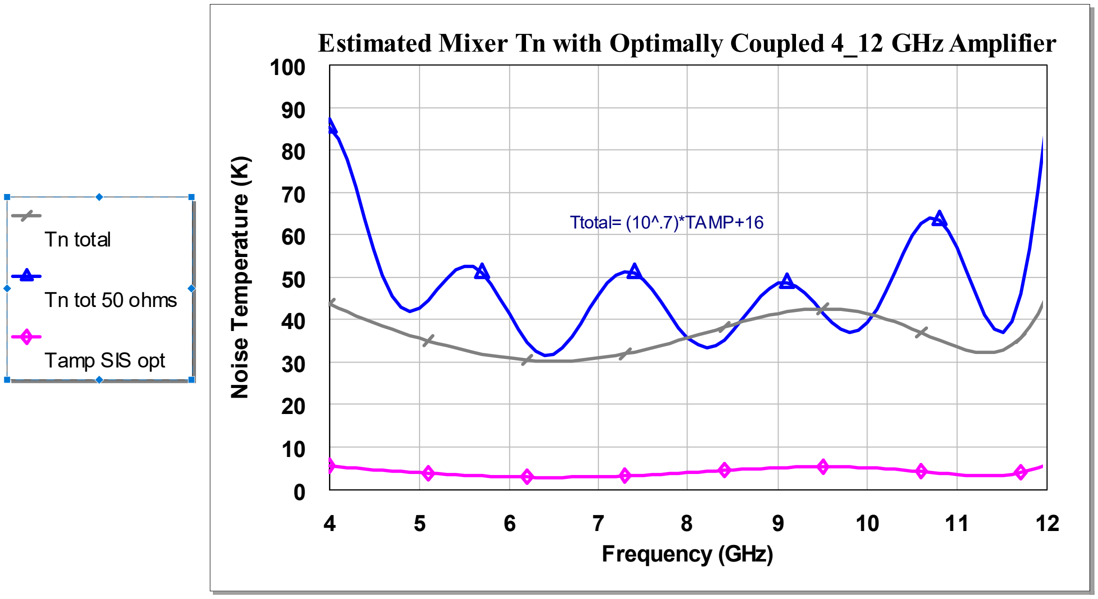
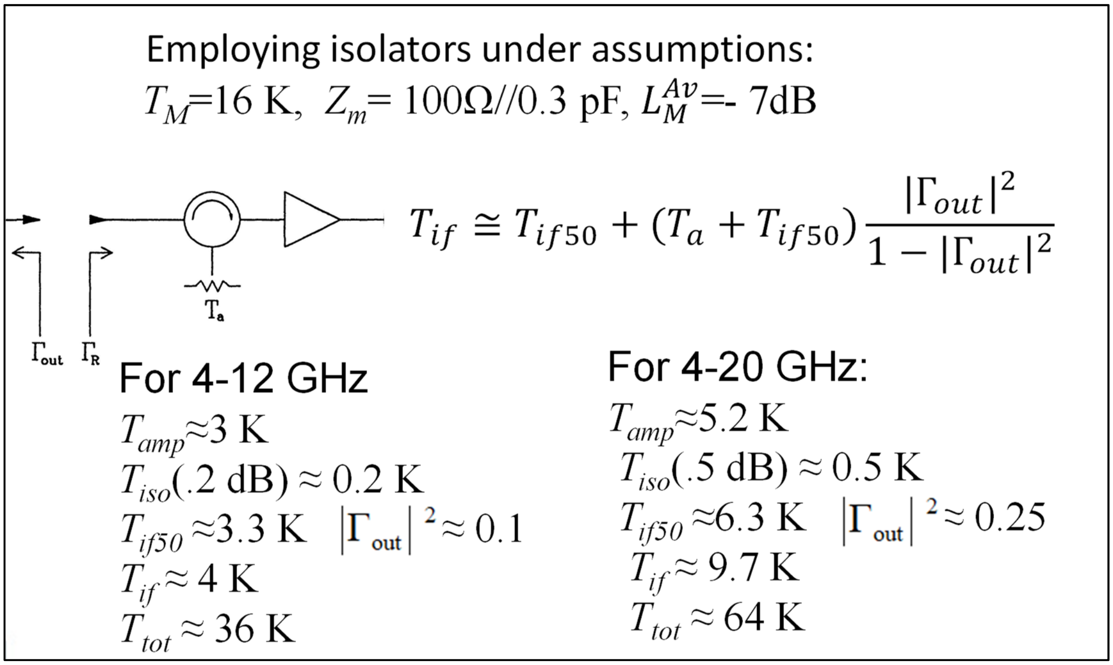


Fig 24. Comparison of modeled SSB noise temperatures of optimally noise coupled SIS/4-12 GHz amplifier tandem (gray) with that presented in Fig. 14 (blue) which is using a 50 Ω connection. The noise of 4-12 GHz amplifier as driven by output admittance Y_M of SIS mixer through and optimal noise matching network (magenta) is also shown. $T_M = 16\,K$ was assumed, the same as for the mixer #2.

These undesirable noise patterns are much larger for wider bandwidth IF amplifiers. For example, the difference between peaks and valley of noise temperatures for SIS/IF amplifier tandems described in Section III are progressively larger for wider IF bandwidths. This observation holds true for any noise matching network inserted between the SIS mixer and the IF amplifier. The computer experiments described in [11] show that the direct integration of 4-16 GHz or 4-20 GHz amplifiers with Band 6 SIS mixer would result in excessive noise temperature variations across the IF band. Furthermore, a direct integration would result also in an excessive gain variation across the IF band as well [11]. That practically limits a direct SIS mixer IF amplifier integration approach to using IF amplifiers of 4-12 GHz bandwidth, or smaller. Indeed, in the currently deployed Band 6 SIS receivers, the mixers are optimally noise matched to 4-12 GHz IF amplifiers only in 6-10 GHz range, even though the IF amplifier exhibit much larger noise bandwidth if measured in a 50 Ω environment [11].

Consequently, extending the IF bandwidths beyond 4-12 GHz requires the use of isolators. An estimation of expected noise penalty for a currently available 4-12 GHz (LNF) and 4-20 GHz (SAO) cryogenic isolators, inserted between SIS mixer and the corresponding IF amplifiers is shown in Fig. 25. The isolators were assumed to be perfectly matched at both ports but exhibit measured cryogenic losses [12]. The assumed average value of SIS mixer output return loss is consistent with the data presented in Section IV. Estimated penalty was computed using “black box “ mixer parameters as determined in section III.


Employing isolators under assumptions:

T_M=16 K, Z_m= 100Ω//0.3 pF, L_M^{Av}=- 7dB

$$T_{if} \cong T_{if50} + (T_a + T_{if50})\frac{|\Gamma_{out}|^2}{1-|\Gamma_{out}|^2}$$

For 4-12 GHz

T_{amp}≈3 K

T_{iso}(.2 dB) ≈ 0.2 K

T_{if50} ≈3.3 K $|\Gamma_{out}|^2 \approx 0.1$

T_{if} ≈ 4 K

T_{tot} ≈ 36 K

For 4-20 GHz:

T_{amp}≈5.2 K

T_{iso}(.5 dB) ≈ 0.5 K

T_{if50} ≈6.3 K $|\Gamma_{out}|^2 \approx 0.25$

T_{if} ≈ 9.7 K

T_{tot} ≈ 64 K

Fig 25. Comparison of expected average SSB noise temperatures of SIS mixer/isolator/IF amplifier tandems for IF bandwidths of 4-12 GHz and 4-20 GHz assuming T_a=4 K.

The estimated penalty of 28 K is large. It could however be reduced if an additional circuit matching output admittance of SIS mixer to 50 Ω were to be introduced. A perfect match, however is not possible, as $|\Gamma_{out}|^2$ is limited by Bode-Fano equation, which states that

$$\int_0^{\infty} ln \frac{1}{|\Gamma(\omega)|} d\omega < \frac{\pi}{RC} \quad . \qquad (2)$$

From (2) the average minimum values of $|\Gamma_{out}|^2$ can be estimated for two cases of Fig. 25, therefore establishing the lower limits on expected average noise temperatures, as well as the estimated noise penalty due to IF bandwidth extension. For R=100 Ω and C=0.3 pF the estimated minimum average values of $|\Gamma_{out}|^2$ are 0.016 and 0.126 for 4-12 GHz and 4-20 GHz bandwidths, respectively. Therefore, assuming a available conversion loss L_M^{Av} = 7 dB, the lower limits on expected noise temperatures are T_{tot} (4-12 GHz) ≈ 33 K and T_{tot} (4-20 GHz) ≈ 55 K, yielding a lower limit on noise penalty due to the IF bandwidth extension of 22 K.

VI. Discussion and Conclusions

The results described above are significant in two main respects: (i) They show clearly the need for an IF isolator (or balanced IF amplifier) if an SIS receiver is to have flat noise temperature over more than about an octave of IF bandwidth; and (ii) they appear to be at variance with the predictions of the performance of SIS receivers based on the widely accepted quantum mixer theory of Tucker [13][14][15]. In particular, the dynamic conductance of the I(V) curve of an SIS around the bias point, normally near the middle of the first photon step, does not appear to be equal to the mixer's output conductance at low IF. Tucker's theory has been the basis for almost all SIS receivers designed in the last fifty years and receivers based on it have generally given the expected results (see, e.g., the ALMA Band 3 and 6 receivers as described in [2]).

Direct mixer-preamp connection

The demonstrated agreement between the modeled and experimental results for a Band 6 SIS mixer and three IF amplifiers with different bandwidths, although Band 6-specific, allows for more general discussion of the limits of broadband noise performance of SIS mixer/HEMT amplifier tandems.

The noise properties of InP HEMTs and their intrinsic minimum noise temperature limits impose in turn restriction on the bandwidth dependent average noise temperature of IF amplifiers. Therefore, any approach to extend the IF bandwidth of SIS mixer receiver will always result in a receiver noise penalty. As the noise temperature of state-of-the-art cryogenic InP HEMT amplifiers cannot be improved, this noise penalty strongly depends on an SIS mixer conversion loss and SIS mixer output admittance. The complex nature of the output admittance of SIS mixer limits how well it can be noise matched over a desired bandwidth to the IF amplifier.

For Band 6 mixer a direct integration of SIS mixer with IF amplifier seems to be a preferable approach but only for up to 8 GHz (4-12 GHz) bandwidth. Progressively poorer noise and gain match between SIS mixer and IF amplifier for larger IF bandwidths (4-16 GHz and 4-20 GHz) creates excessive noise and gain patterns and therefore cryogenic isolators have to be used, or alternatively balanced IF amplifiers. For 4-12 GHz IF bandwidth and the best available SIS mixers, average noise temperatures of about 35 K SSB are possible. This noise temperature estimation does not significantly differ between an "integrated" and "thru isolator" approach, although the component count strongly favors the first approach. However, for the Band 6 SIS mixers used in this work doubling the IF bandwidth from 4-12 GHz to 4-20 GHz while using the current state-of-the-art isolators would result in a substantial receiver noise penalty, as much as ~20-30 K. This noise penalty would of course be reduced when mixers with lower conversion loss were used.

The complex nature of Band 6 SIS mixer output admittance limits the IF bandwidth extension for a directly integrated version. However, a smaller RC product of the SIS mixer output admittance could facilitate a larger IF bandwidth. This especially might be true for SIS mixers for higher ALMA bands.

Deviation from the expectations of Tucker's theory

The measured IF noise patterns for Band 6 SIS mixer are highly repeatable for different LO settings across the full RF band. It implies that SIS mixer IF output admittance is not a strong function of radio frequencies, indicating in turn that sideband RF terminations do not vary strongly with LO frequency. Some IF noise traces deviating significantly from prevailing noise patterns seem to be singularly a LO sideband noise problem.

Some Band 6 SIS mixers, however, exhibit effects, which do not have satisfactory explanation. The real part of output admittance computed from SIS mixer theory is several time smaller than that estimated from the noise pattern measurements (Fig. 19). Furthermore, some Band 6 mixers demonstrate negative dynamic conductance, usually at the lower LO frequencies, as shown in Fig.17. The measured output conductance of the SIS mixers used in these experiments, however, is positive and substantially higher than the dynamic conductance would suggest, even at low IFs where the incremental conductance of the I(V) curve is expected to be close to the IF output conductance. However, the presence of this negative I(V) conductance correlates with the propensity for parasitic oscillations at frequencies well below the IF band, typically around 1 to 2 GHz. This oscillation can be easily cured by adding a lossy frequency selective network to the matching network between SIS mixer and IF amplifier. Therefore, the real part of pumped SIS mixer output admittance must assume negative values at frequencies of possible parasitic oscillations. Surprisingly, the check of ORL of these mixers in 4-12 GHz IF frequency range using the set–up of Fig. 21 revealed no presence of such effects.

The apparent disagreement between these measurements and the predictions of Tucker's quantum mixer theory is currently being explored.

The findings from this study will serve as valuable input to the ALMA Development project to design and build a Band 6 Version 2 prototype receiver with wider instantaneous bandwidth and improved performance compared to Version 1.

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