Improved Multi-octave 3 dB IF Hybrid for Radio Astronomy Cryogenic Receivers

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***Abstract*—Modern mm and sub-mm ultra low noise receivers used for Radio Astronomy have evolved to provide very wide instantaneous bandwidth. Some of the configurations used in present cryogenic front-ends, like sideband separating mixers and balanced amplifiers, need 90º 3 dB hybrids at the IF, typically in the 4-12 GHz band. There are commercially available devices covering this band with good ambient temperature characteristics, but poor cryogenic performance. We describe the design, construction and measurement of a multioctave stripline hybrid for the 4-12 GHz band specially conceived to perform reliably when cooled to 15 K. The coupling and reflection show very little temperature dependence.**

A balanced cryogenic amplifier was assembled with two 3 dB hybrid units and available amplifiers (~4.5 K noise temperature) designed and built in-house for ALMA. This device is critically compared with a single ended amplifier and with an amplifier with an input isolator. The latter is the typical arrangement of the IF of radio astronomy receivers. The balanced option shows an advantage of 2.8 K in noise with less sensitivity to input mismatches.

***Index Terms*—Balanced amplifier, cryogenic receivers, hybrid coupler, low noise.**

I. Introduction

A classical problem of millimeter and submillimeter radio astronomy receivers is how to match the mixer to the IF amplifier. The trend on the past decade has been to increase the instantaneous IF bandwidth as required for the achievement of new and more ambitious scientific goals, taking advantage of the continuous evolution of the analog and digital backends. For the HERSCHEL ESA mission, which will be launched this year, it was decided to set the value of the instantaneous IF bandwidth at 4 GHz. Later, for the development of ALMA[1], now in construction, it was decided to use even a wider 8 GHz instantaneous IF in the 4-12 GHz band. The wide fractional bandwidths involved imposed an important challenge in both sides, mixers and IF amplifiers. For the low noise amplifier (LNA) side, it soon became clear that obtaining simultaneously low reflection and noise in very wide bands was not an easy task. In the case of a traditional receiver, the mixer and the IF amplifier are different modules, sometimes cooled at different physical temperatures and connected by coaxial cables. If no action is taken, the ripple in noise and gain caused by the reflections at both sides of an electrically long cable is an important issue which may deteriorate the overall sensitivity. One approach, followed by some groups [1], [2] has been to eliminate the connecting cable by integrating the amplifier and the mixer. This solution, although very successful in some cases, has some practical difficulties, and has not been universally adopted. The other common approach has been to use wideband cryogenic ferrite isolators between the mixer and the LNA. There are now commercial cryogenic isolators available for the 4-8 GHz and 4-12 GHz bands, developed by the needs of HERSCHEL and ALMA projects, which have become a common building block in modern receivers. The performance obtained with the isolators is quite good in terms of reflection and isolation, but not as good in terms of insertion loss, particularly in the case of the 4-12 GHz band. The effect of the loss is especially painful, since part of the effort employed in obtaining very low noise state of the art devices is lost in the passive component. The motivation of the present work was to explore the possibilities of a balanced amplifier as an alternative to the isolator, with the idea of reducing the noise while keeping a good input reflection. Balanced amplifiers have been used for many applications since their introduction more than forty years ago, but not many have been reported for practical cryogenic applications [3].

The first thing needed for demonstrating the balanced amplifier is a suitable wideband cryogenic 90º 3 dB hybrid. Such a device may have other applications in radio astronomy receivers, like for example for the IF port in a 2SB image rejection receiver. There are some commercial devices available for the 4-12 GHz band which can be cooled, but the results obtained in our experiments showed degradation of their cryogenic performance. Furthermore, commercial units are not conceived to survive the aggressive thermal cycles from ambient to cryogenic temperature. Due to these limitations, it was decided to develop and build hybrids specially suited for cryogenic operation, improving the performance and reliability. The prototypes developed were used for the demonstration of a balanced amplifier and for the

Manuscript received 19 April 2009. This work was supported in part by the European Community Framework Programme 7, Advanced Radio Astronomy in Europe, grant agreement no.: 227290

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[1] Atacama Large Millimetre Array, a future radio astronomical interferometer now in construction in Chile.

comparison of the performance obtained with the classical amplifier isolator combination.

II. Hybrid Coupler Design and Fabrication

The simplest way to build a directional coupler of strong coupling is to use coupled transmission lines manufactured in stripline technology. The proposed 4-12 GHz hybrid design is focused in an offset broadside coupled stripline structure, using Mylar as a dielectric separation layer (see Fig. 1). To get the required bandwidth it is necessary to use three sections of $\lambda/4$ coupled lines [4], so the coupling has a contained ripple across the band.

The design has been done using the 2.5D EM tool Momentum (from HP EESOF ADS). The dielectric constant of the substrates is ε_r=2.94, with a thickness of 508 µm (20 mils), while the separation film is 23 µm thick, with ε_r=3. The critical dimensions of the hybrid are located in the central $\lambda/4$ section (see Fig. 1). This section has the narrowest line widths (w_2=159 µm) and an offset between the coupled lines (in the initial design) of wo_2=50 µm. This offset is essential for tuning the coupling factor.

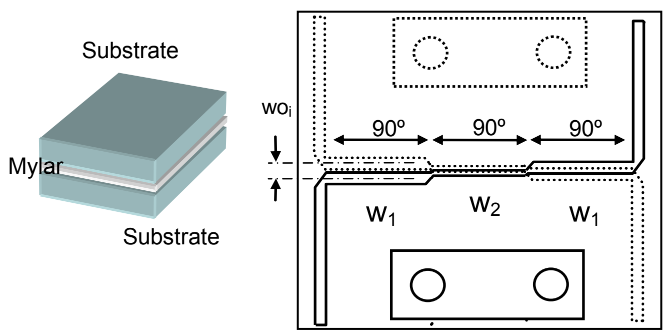

Fig. 1. Schematic of the three $\lambda/4$ sections hybrid coupler. The structure (substrates plus Mylar separator) is 21.4 × 16 × 1.073 mm. Mylar film is 23 µm thick.

The hybrid must operate at 15 K without degradation; therefore all the materials used in the fabrication process must have high thermal stability. The substrate selected is RT/Duroid[2] ® 6002, which has been previously used in other cryogenic designs, even for space applications, and whose performance and stability are well demonstrated. The thermal coefficient of the dielectric, as given by the manufacturer, is +12 ppm/ºC and the thermal expansion coefficient is 16 ppm/ºC (x,y axis) and 24 ppm/ºC (z axis). The cupper metallization covers one side only and is 0.5 oz/ft^2 thick.

The coupling factor is strongly affected by the distance between substrates. To keep this separation stable when cooling the structure, the chassis of the coupler has been built in aluminum alloy, whose thermal expansion coefficient (23 ppm/ºC at 25ºC) almost perfectly matches the z axis coefficient of the substrate. Mylar is chosen as separation layer because its dielectric constant is very similar to that of the Duroid, and it has higher rigidity and superior thermal stability (0.17 ppm/ºC) than other similar polymers [5].

The whole circuit has been manufactured using a laser milling machine (LPKF[3] ProtoLaser 200). Its resolution is better than needed and it allows etching and cutting the substrate in the same operation making the alignment of the coupled lines very accurate. Fig. 2 shows one half of the built coupler with the aluminum chassis and connectors.

An important practical problem is the reliability of the contact between the substrates and the input/output connectors. Commercial hybrids use standard SMA connectors directly soldered to the substrates. The mechanical stress produced by the variation of temperature from 300 K to 15 K can easily lead to failures in the solder joints after repeated cycles. To minimize this risk we have used connectors with sliding central pin (R.125.410.000 made by RADIALL[4]) which let slight shifts of the central pin alleviating the mechanical stress.

Another problem found was the electrical discontinuity between the coaxial connector and the stripline. The discontinuity was tuned out to obtain a -22 dB of return loss by means of an inductive gap between the flange and the substrate.

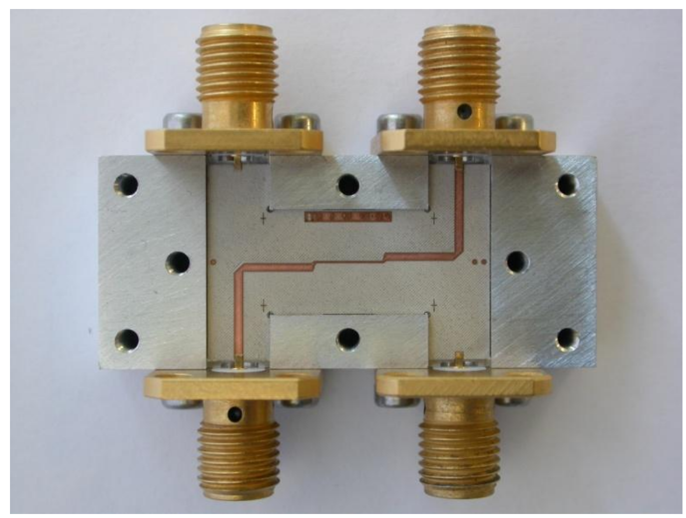

Fig. 2. Assembled coupler (one half shown). Mylar sheet and upper half of the stripline substrates are removed.

III. Hybrid Coupler Measurements and Results

Measurements at 300 K agree with Momentum simulations: return loss was better than -22 dB and the directivity was higher than 20 dB. Only the coupling factor was 0.15 dB lower than expected probably due to manufacturing tolerances of the Mylar sheet thickness (which is 20% as specified by the supplier). To compensate the reduction of the coupling factor, the offset of the central lines, wo_2, was reduced from 50 µm to 0 µm. With this modification the desired coupling factor was achieved.

The measurements were made using a cryostat calibrated at 300 K and at 15 K with SOLT standards, and the results are compared in Fig. 3. Almost no degradation in performance is observed when cooled. At 15 K the measured worst case

[2] Rogers Corporation Advanced Circuit Materials Division, Chandler, AZ 85226, USA.

[3] LPKF Laser & Electronics AG, Garbsen 30827, Germany.

[4] RADIALL SA, 93116 Rosny Sous Bois, France.

amplitude unbalance is ±0.3 dB and phase unbalance is ±2º, in the 4-12 GHz band. Table I compares this results with the best commercial hybrid available, tested in the same setup.

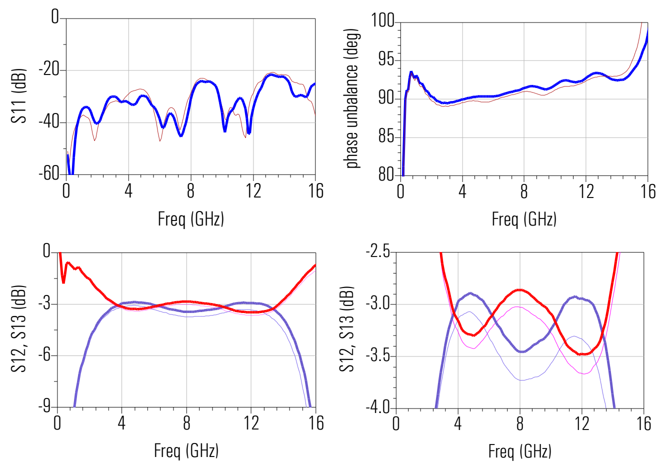

Fig. 3. Measurements of the hybrid at 15 K (thick lines) and 300 K (thin lines). Note the almost invariable behavior with temperature due to the careful selection of components and technologies.

TABLE I COMPARISON WITH COMMERCIAL UNITS

Measurement @ 15 K, 4-12 GHz	CAY design (average of 3 hybrids)	Best commercial unit
Return loss	<-22 dB	<-19 dB
Amplitude unbalance	±0.3 dB	±0.9 dB
Phase unbalance	±2º	±3º

The key of the high thermal stability of the hybrid is the careful selection of materials, as stated in section II. The aluminum chassis and substrate material have matched thermal expansion coefficient in the z axis, therefore they shrink approximately by the same amount when cooled and hence the distance between coupled lines remains almost constant with temperature.

The overall dissipative loss introduced by the hybrid has been estimated by calculating the equivalent insertion loss, L_{eq}, defined by:

$$L_{eq} = 10 \cdot \log_{10}\left(|s_{11}|^2 + |s_{12}|^2 + |s_{13}|^2 + |s_{14}|^2\right) \qquad (1)$$

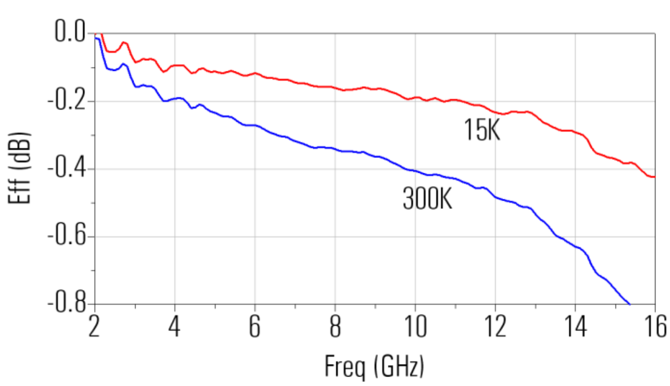

Fig. 4. Equivalent insertion loss obtained with (1) from measurements of the S parameters of the hybrid coupler.

The dissipative loss at 15K, shown in Fig. 4, is better than 0.2 dB in the 4-12 GHz band. This value is much lower than the typical insertion loss of a cryogenic isolator in the same band.

IV. Realization and Measurement of a 4-12 GHz Balanced Amplifier

State-of-the-art cryogenic low noise amplifiers in the 4-12 GHz band have been designed and built in our labs for the IF of band 9 of ALMA front-ends [6]. Some pre-production units are available at our premises and two of them, randomly chosen, were used together with two 90º hybrid coupler prototypes of the type described here, to assemble a balanced amplifier. A picture of one of the ALMA amplifiers is shown in Fig. 5. The balanced amplifier can be seen in Fig. 6, and a schematic is depicted in Fig. 7.

The amplifiers used incorporate InP NGST [7] devices and have an average noise temperature around 4.5 K with 34 dB of gain and -4 dB and -15 dB of input and output return loss (worst case) respectively. Note that the poor input reflection is due to the compromise made in optimizing the performance, with emphasis in the noise, for a very wide band. To avoid the mismatch between the SIS mixers and the IF amplifiers in ALMA receivers, it was decided to use them in combination with PAMTECH[5] cryogenic isolators.

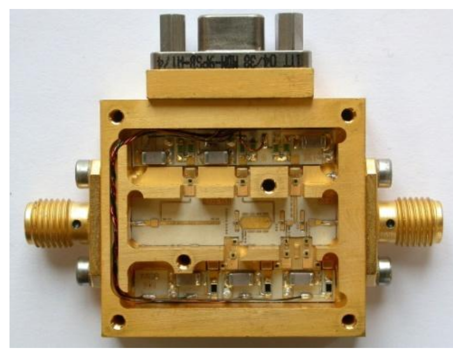

Fig. 5. ALMA band 9 4-12 GHz production cryogenic amplifier.

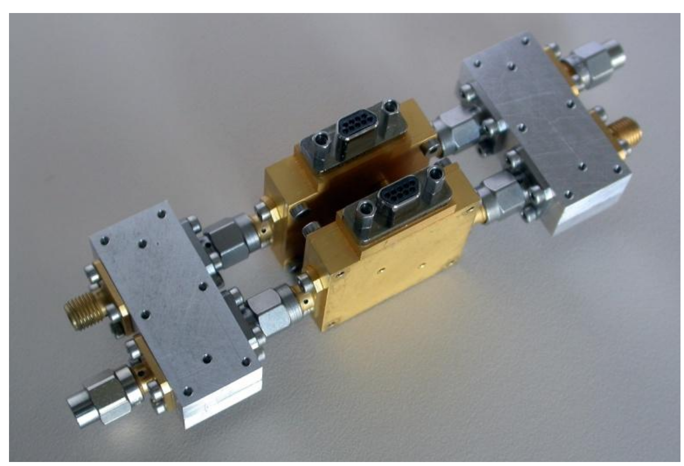

Fig. 6. Prototype 4-12 GHz cryogenic balanced amplifier made up of two 3 dB hybrids as described here and two ALMA-type amplifiers.

[5] Cryogenic isolator of the type currently used in ALMA receivers made by PAMTECH (Passive Microwave Technology, Camarillo CA 93012 USA).

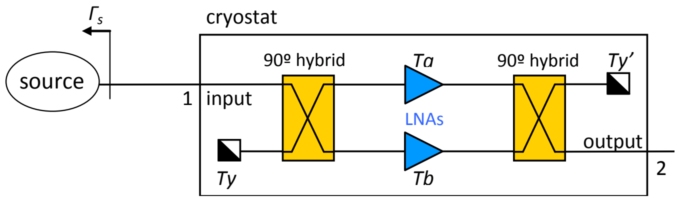

Fig. 7. Schematic of a balanced amplifier.

Fig. 8 presents the experimental setup inside the cryostat. Noise and gain were measured using he cold attenuator method, with an estimated absolute accuracy of ±1.4 K (3σ), and repeatability one order of magnitude better [8]. This method allows good accuracy even for amplifiers with high input reflection, and can be implemented with commercially available equipment (Agilent N8975A).

Fig. 9 shows the results of the three configurations. The first stage bias was optimized for low noise in all cases, while the bias of the second and third stages of both amplifiers in the balanced configuration was chosen to minimize the unbalance and thus optimize the overall noise as stated in section VI. B. Note the clear advantage in noise temperature (2.8 K in average) of the balanced amplifier over the cryogenic isolator due to the lower loss of the hybrid. The input return loss (worst case in the band) for both configurations is better than -15 dB whereas for the amplifiers is only about -4 dB.

V. Noise Performance for a Mismatched Input Termination

The practical advantage of the balanced amplifier over an amplifier with the best commercial available cryogenic input isolator has been demonstrated by measurements with a matched input termination, in the previous section. However, in a real receiver, the input impedance seen by the amplifier may be quite far from the matched condition. In the case of an SIS mixer, for example, the impedance presented at the IF output port depends on many factors, including the LO frequency, and typically sweeps a wide range of complex values across de IF band. The theoretical calculation of the noise parameters of an amplifier with an isolator at the input is possible without knowing the detailed noise parameters of the amplifier [9]. However, for the balanced amplifier, the complete information of noise parameters of the amplifier and its input reflection coefficient is needed in order to estimate the noise parameters of the combination [10]. As accurate measurements of noise with mismatched input terminations were not possible in our cryogenic measurement system, a model was used to predict the behavior under different circumstances. The three configurations (stand-alone, input isolator and balanced amplifier) were simulated at 15 K for a range of input impedances.

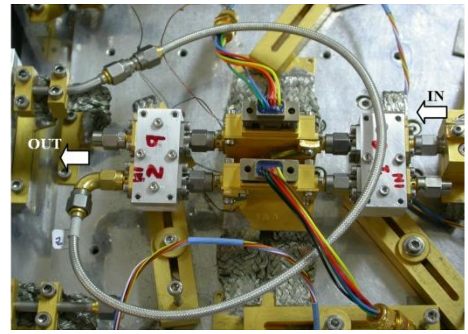

Fig. 8. Balanced amplifier inside the measurement cryostat.

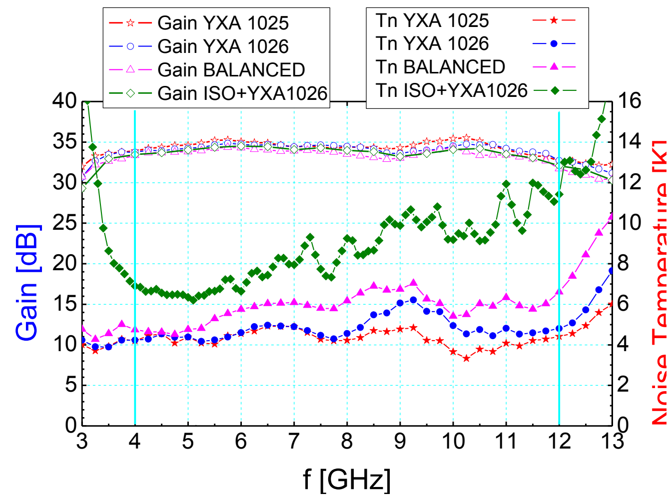

Fig. 9. Comparison of the noise temperature and gain for a balanced amplifier, amplifier with an input isolator and the individual amplifiers. Measurements were taken at 15 K.

Fig. 10 shows the results obtained for three different values of a pure real input termination connected by a length (10 cm) of 50 Ohm ideal line to the input of each configuration. To avoid confusion with other effects, the simulation was performed with a realistic model of the amplifier [6] but with ideal isolator and 3 dB hybrids (without loss). The length of 50 Ohm line was included to easily visualize the ripple pattern appearing in the case of the single ended amplifier caused by multiple reflections. Note that this ripple is totally eliminated, as expected, by the other configurations. The most interesting feature visible in Fig. 10 is that the balanced amplifier and the input isolator configurations are not totally equivalent; being the balanced the one showing lower noise under mismatched conditions. This is due to the lower value of the noise parameter R_n for the balanced amplifier at 15 K. Note that the prediction of this model assumes all the components cooled to the same physical temperature of 15 K. The situation may be the opposite, for example, if the termination of the isolator is cooled to a physical temperature below approximately 7 K.

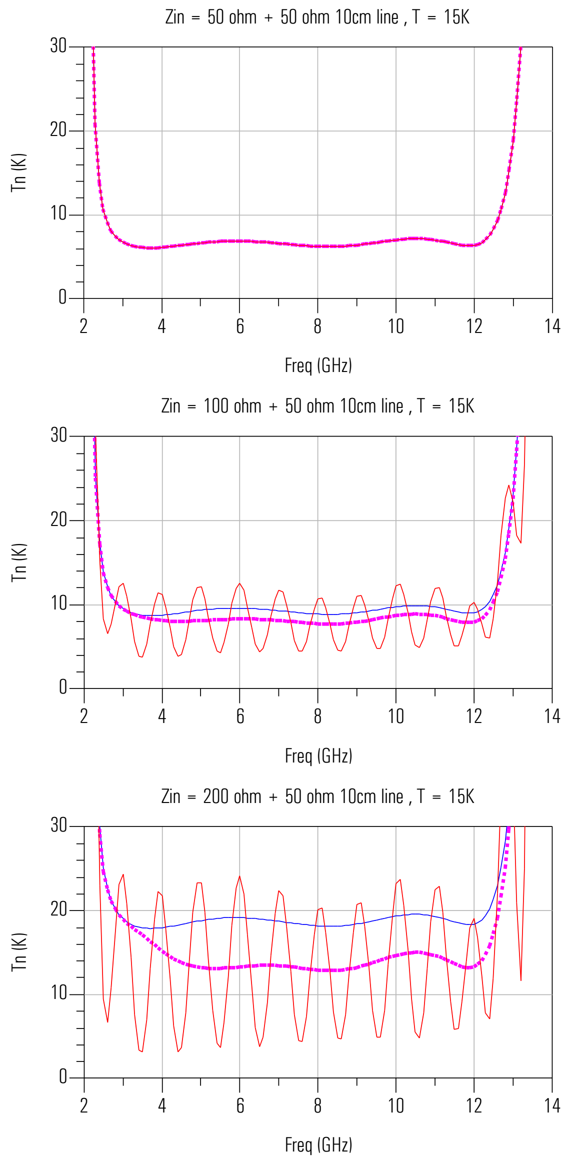

Fig. 10. Simulations at 15 K of the impact in noise temperature of the variation of the input load (50-200 ohm) placed after an ideal 10 cm line. Single-ended amplifier is in red, balanced amplifier is in magenta, amplifier with input isolator is in blue. The hybrid and isolator are assumed ideal.

VI. Disadvantages of a Balanced Configuration

A balanced configuration has an obvious drawback: its inherent complexity, needing two couplers and two amplifiers. This usually reflects also in an increased cost. Another consequence which may be significant for some applications is the higher power dissipation. There are other potential weaknesses which will be analyzed below, like the sensitivity of noise to amplifier gain and/or phase unbalance, or the variation of the output reflection with the input load.

A. *Effects of amplifier gain and phase unbalance*

In an ideal balanced amplifier the two branches are identical. In practice, however, some phase and gain unbalance is always present with the consequence of degradation of the performance.

In terms of noise temperature, the main effect is that the thermal noise from the termination of the input hybrid does not null at the output, causing an increment in the noise of the system. It can be shown that, for an ideal but not perfectly balanced amplifier, the noise temperature can be expressed as:

$$T_n(\Delta g, \Delta p_g) = \frac{T_y \cdot (1+\Delta g^2 - 2\Delta g \cdot \cos\Delta p_g) + 2T_a + 2T_b \cdot \Delta g^2}{1+\Delta g^2 + 2\Delta g \cdot \cos\Delta p_g} \tag{2}$$

where Δg is the module gain unbalance (g_a / g_b), Δp_g is the phase gain unbalance ($p_{gb} - p_{ga}$ in radians), T_a and T_b are the noise temperatures of the individual amplifiers and T_y is the physical temperature of the termination of the input hybrid.

Fig. 11 shows plots of the noise temperature as a function of the gain and phase unbalance. In case of equal phase, the noise temperature increases relatively fast as we depart from the balanced situation, but it is bounded: for a perfect balance, T_n is the average noise temperature of the component amplifiers, and at worst, it is always lower than the sum of the noise temperatures of both amplifiers plus the physical temperature of the hybrid. The sensitivity of the noise temperature to a small phase unbalance is lower than in the case of a gain unbalance, but it is not bounded.

In our case, the prototype hybrids, as explained in section III, exhibit a very good repetitivity, with ±0.3 dB amplitude unbalance and ±2º phase unbalance, so the impact in noise in the balanced structure can be neglected. In practice lots of amplifiers with the same type of devices and following the same design and manufacturing procedures use to have a relatively small dispersion in phase and gain. For example, the mass production units of band 9 ALMA IF preamplifiers, despite the intensive tuning needed in some cases, show a maximum gain and phase excursion of 3 dB and 22º respectively (for a total of 50 samples). This translates for a worst case combination in an increment of ~1.9 K in noise at the most unfavorable frequency point according to (2). However, in some cases it may be advisable to improve the balance of the amplifier.

A simple and effective way of doing it is to adjust the bias of the last stages of the amplifiers (keeping fits stage bias values compliant with the low noise specifications). This method is illustrated in Fig. 12, which shows the variation of the noise temperature of the balanced structure with the bias settings of stages 2 and 3 of one of the amplifiers. For the particular case of the amplifiers randomly chosen for our balanced structure, the unbalance was negligible, so only 0.2 K of improvement (over a T_n of 6 K) was achieved experimentally by tuning the bias.

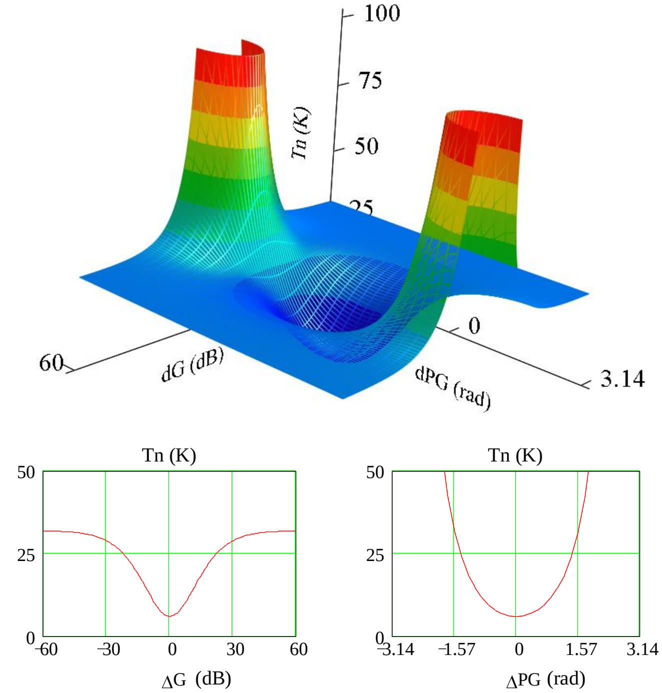

Fig. 11. Noise temperature for a balanced amplifier with amplifier temperatures T_a=T_b=6 K and physical temperature T_y =15 K according to (2). On the top, T_n vs Δg (in dB) and Δp_g. On the bottom, two sections of the 3D figure, T_n vs. Δg when Δp_g =0 (on the left) and T_n vs. Δp_g when Δg =0 (on the right). The sensitivity to small changes is higher for the gain unbalance.

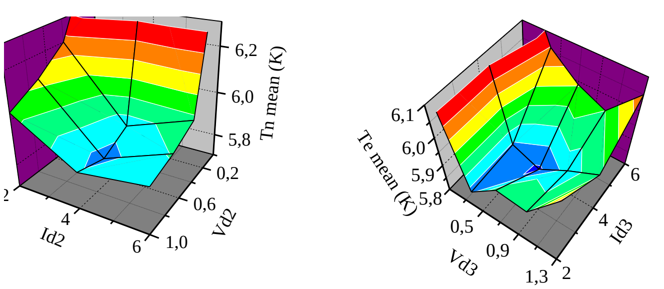

Fig. 12. Measurements of noise temperature of the balanced amplifier for different bias settings in stages 2 and 3. It is possible to improve the balance of the structure by changing slightly the gain of the individual amplifier and thus, optimize the noise temperature.

B. Effects of input load on output return loss

Another difference between balanced amplifiers and amplifiers with input isolator is that the output return loss of the input isolator is insensitive to changes in the input load. This was experimentally tested at room temperature by placing a sliding short at the input of the different configurations. The results varying the length of the short are shown in Fig. 13. Stand-alone and balanced structures display a similar dispersion of the S_{22} plots, whereas the isolated amplifier exhibits an almost invariable behavior. Still the results of the balanced amplifier are better in all cases due to the superior output reflection of the hybrids respect to the stand-alone amplifier.

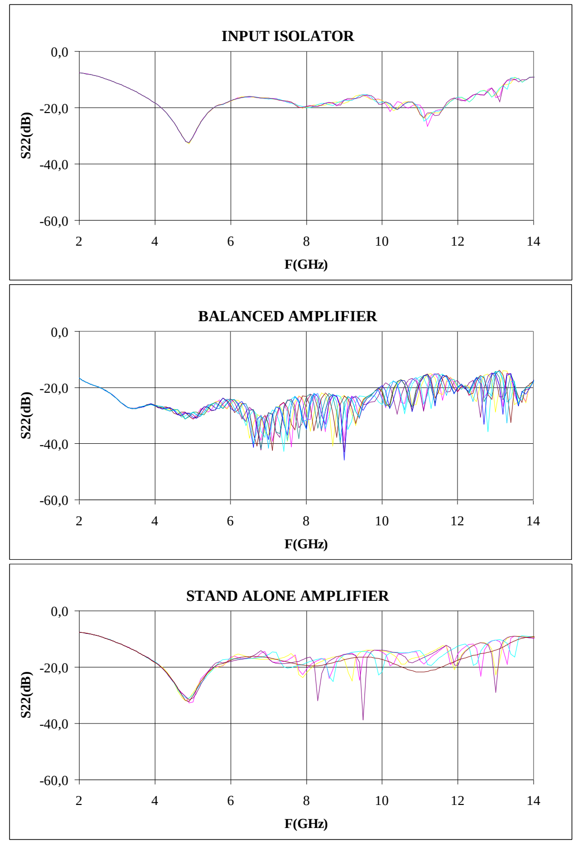

Fig. 13. Measurements of output reflection for different lengths of a sliding short-circuit at the input in the three amplifier structures. Note that the balanced amplifier is not immune to this change in input loading, but nevertheless its return losses are still always better than the stand-alone amplifier.

VII. Conclusion

A cryogenic 3 dB 90º hybrid optimized for cryogenic applications has been designed built and characterized. The result is a reliable unit, ease to assemble, repeatable and with very stable performance from ambient temperature to 15 K. The goal of obtaining lower insertion loss than in a commercial cryogenic isolator from the same band has been achieved. A cryogenic balanced amplifier using two randomly chosen standard ALMA production amplifiers has been assembled and tested to verify its advantage, obtaining an improvement of 33% in noise temperature respect to the input isolator configuration. Furthermore, the noise temperature of a balanced amplifier measured at 15 K is less sensitive to input mismatches. In addition, the effect of the gain unbalance between the component amplifiers, and its effect in increasing the noise of the balanced configuration has been estimated. Despite the fact of the additional complexity and power dissipation, the demonstration balanced amplifier shows a clear advantage in performance respect to the traditional isolator and amplifier configuration.

Acknowledgment

The authors wish to thank R. García-Nogal for his help in manufacturing the prototypes used in this work.

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