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Cryogenic Amplifiers for Jansky Very Large Array Receivers

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Abstract—**The Very Large Array (VLA) has been recently renamed the Jansky Very Large Array (JVLA) to honor Karl Jansky, the founder of radio astronomy. It has been undergoing a major expansion since 2001 to improve both the frequency coverage and sensitivity. This project previously known as Expanded VLA (EVLA) required new designs of cryogenic amplifiers to provide continuous coverage from 1 GHz to 50 GHz in eight bands with possible best noise temperature. This paper describes the device models and design approach used, provides examples of measured and modeled results, and presents repeatability of measured performance on large samples of amplifiers. These amplifiers in majority of the bands exhibit the best noise performance ever demonstrated at these frequencies, typically about five times the quantum noise hf/k, when measured at physical temperatures of 15-20 K.**

Keywords: low noise amplifiers; heterostucture field effect transistors; high electron mobility transistors; noise models; noise parameters; low noise receiver; radio astronomy; radiotelscopes.

I. INTRODUCTION

The JVLA is an aperture synthesis imaging array operated by National Radio Astronomy Observatory near Socorro, New Mexico, USA [1]. The cryogenic receivers cover 1-50 GHz frequency range in eight bands. The first three are of octave bandwidths covering 1-8 GHz, the following four have approximately waveguide bandwidths (8-12, 12-18, 18-26.5, and 26.5-40 GHz) and the last covers 40-50 GHz [1]. The VLA (precursor of JVLA), dedicated in 1980, originally had receivers using cryogenically cooled parametric amplifiers and converters in S-, C-, and K_u- bands and Schottky diode mixers in K-band [2]. Soon after the dedication, the amplifiers operating at cryogenic temperatures, using III-V field effect transistors (FETs) and later heterostructure field effect transistor (HFETs, HEMTs), started replacing the old systems improving not only the frequency coverage but also allowing for the addition of new frequency bands (most notably X-band receivers for the Voyager at Neptune fly-by in 1989 and Q-band receivers in early 1990's). Several generations of cryogenic amplifiers using different devices employed at the Array have been described in [3]. It has been observed that FETs (HFETs) from different wafers manufactured using similar technologies exhibit very different performance at cryogenic temperatures, even if they had very similar room temperature performance [3]. As a result, at any given time HFET devices from a single wafer (or set of wafers manufactured at the same time) that exhibited exceptionally good cryogenic performance were used in the construction of these amplifiers. For example, Voyager/Neptune amplifiers used AlGaAs/GaAs, 0.25 micron gate length HFETs manufactured for NRAO and JPL by General Electric Military Electronics Division [4]. Almost all the cryogenic receivers installed in 1990's have used amplifiers built with 0.1 micron gate length InP HFETs manufactured by Hughes Research Laboratories [5], [6]. The same devices were used in the construction of Wilkinson Microwave Anisotropy Probe radiometers [7]. The most recent in this series of "radio astronomy golden wafers" are the so-called "cryo3" wafers produced by the Northrop Grumman Space Technology (NGST) in 1999 for the Jet Propulsion Laboratory Deep Space Network (JPL DSN) under the Cryogenic HEMT Optimization Program (CHOP). These wafers contain tens of thousands of AlInAs/GaInAs/InP HFET chips with 80 nm gate length and different device peripheries.

In Section II, the dc, small signal, and noise equivalent circuits of NGST "cryo3" devices are reviewed. A general review of performance of amplifiers and comparison of their performance with even more advanced InP HFETs technologies is provided Section III. Examples of realized amplifiers and their measured and modeled performances are described in Section IV. Examples of repeatability of measured performance are also given. The concluding remarks are offered in Section V.

II. "CRYO3" WAFER INP HFETS

The dc properties of "cryo3" InP HFETs were extensively reviewed in [8]. Examples of the dc measured trans-conductance as a function of drain current at the ambient temperatures of 297 K and 15 K, adopted from [8], are shown in Fig. 1. The key observation is that for very low current densities per unit gate width, the transconductance g_m more than doubles on cooling, while at the current densities corresponding to maximum g_m increases only by 15 percent. Such a property, as it was observed before [3], [4], is indicative of good cryogenic noise performance and it is easily interpretable in terms of noise model [9] as demonstrated in [3]. In fact, the bias optimal from the point of view of minimum noise temperature at any frequency is that minimizing the value of [3]:

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$$\mathrm{f}(V_{ds},I_{ds}) \cong \frac{\sqrt{I_{ds}}}{g_m}\ . \tag{1}$$

The optimal bias at cryogenic temperatures for these devices typically falls in the range of 25-35 mA/mm for drain currents and .7-.9 V for drain voltages.

The equivalent circuits of these devices having 200 micron wide periphery have been studied before [11]. The equivalent circuit presented in [11] scales quite well for smaller device peripheries. The designs of amplifiers as well as the modeling results presented in Section II and IV rely on the small signal and the noise model developed in [9]. An example of the small signal and noise model for an 80 micron wide device is shown in Fig. 2.

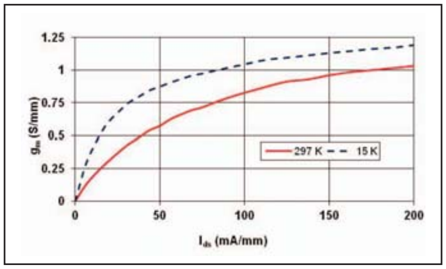

Figure 1. Transconductance for a sample device from cryo3 wafer measured at ambient temperatures of 297 K and 15 K (after [8]).

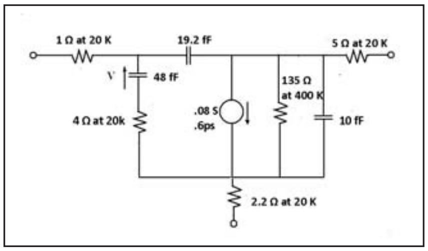

Figure 2. Small signal and noise equivalent circuit of "cryo3" 80 micron wide device at Ta=20 K and low noise bias used in the design of K- and Ka-band JVLA amplifiers. Circuit elements representing bond wires and bond pads were omitted.

III. OVERVIEW OF JVLA AMPLIFIER NOISE PERFORMANCE

Knowledge of small signal and noise model, such as presented in Fig. 2, allows for the determination of the minimum noise measure of a device defined as:

$$M_{\min} = \left(\frac{T_n}{1 - \frac{1}{G_a}} \right)_{\min} , \tag{2}$$

where T_n is the noise temperature and G_a is the available gain of an individual device. The noise temperature of a properly designed low-noise, high-gain, wide-band amplifier should touch upon the minimum noise measure of a device used at some frequencies within its band. The measured noise temperatures of JVLA amplifiers are plotted in Fig. 3 along with the expected minimum noise measure, predicted in 1991, for a hypothetical cryogenic InP HFET [12]. Measured noise temperatures of representative amplifiers covering 4-50 GHz frequency range are shown. Indeed, the noise temperatures of JVLA amplifiers for higher frequency bands follow that 20 year old prediction quite well, typically exhibiting noise temperatures at a level of 4-5 times *hf/k.* At X-band and lower frequencies, the noise contribution of ohmic losses (coaxial connectors, matching structures, bias circuits, and hybrids) to the amplifier noise temperature is relatively larger than at higher frequencies. Therefore, typical noise temperatures of 1-2 GHz and 2-4 GHz amplifiers are about the same level at about 3.5-4.5 K.

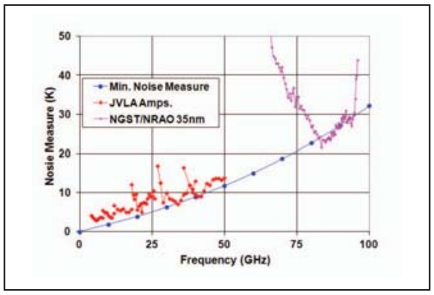

Figure 3. Comparison between the prediction for the minimum noise measure of cryogenic InP HFET (1991, [12]) and the typical noise temperatures measured for JVLA amplifiers. For comparison the noise temperature measured for NRAO/NGST MMIC design using 35 nm gate length HFETs is also shown [13].

Recently, the research into more advanced heterostructures with improved electron transport properties and aggressive scaling of gate length have produced HFETs with considerably higher f_t and f_{max} frequencies (for example [13],[14]) compared to those of "cryo3" wafers devices, produced in 1999. The best measured result for frequencies below 100 GHz [13] using 35 nm gate length technology is also plotted in Fig. 3. Surprisingly, its measured noise temperature falls on the same minimum noise measure curve as the noise temperatures of JVLA amplifiers. It indicates that using current 35 nm technology at frequencies below 50 GHz might not necessarily result in achieving noise temperatures lower than those already demonstrated for "cryo3" devices.

A simple approximate expression for the minimum noise temperature of an intrinsic FET takes the form [3]:

$$T_{\min} = \frac{f}{f_{\max}} \sqrt{T_a T_d} \tag{3}$$

where all the symbols have their usual meaning. For the noise model of [9] to correctly account for the measured noise temperature of the amplifiers using 35 nm HFETs, the equivalent drain temperatures T_d=1400K had to be assumed [13]. It is in contrast to T_d=400K (Fig. 2) or even lower values

[11] required to explain the measured noise temperatures of amplifiers with "cryo3" devices. It follows from (3) that even doubling the maximum frequency of oscillations f_{max} for an individual device would result in little, if any, improvement in T_{min} if it also results in such a large increase in T_d. It is not known whether short channel effects in these developmental 35 nm gate length HFETs can explain the experimental results. Further research is needed on what seems to be already limiting the achievable noise performance of InP HFET technology.

IV. EXAMPLES OF JVLA AMPLIFIERS

A sample set of JVLA amplifiers is shown in Fig. 4. Up to 12 GHz, the amplifiers use field replaceable K-connectors at the input and output. The 12-18 GHz amplifier has WR62 waveguide input and K-connector output. At higher frequencies, WR-42, WR-28 and WR-22 waveguide inputs and outputs are used. For waveguide units, a plane of an input flange can be rotated by 180 degrees to allow for more options in dewar design. Red light emitting diodes, clearly visible in Fig. 4, are used to ensure that the active devices do not exhibit memory effects at cryogenic temperatures [3], [4]. However, the noise temperature of "cryo3" devices is not sensitive to illumination, although InP HFETs from other wafers do exhibit this property.

All the JVLA receivers, but for first two bands, have cryogenic isolators located at the input of each LNA [1]. This is required to reduce the standing waves in the front end optics and to reduce the cross-channel leakage between two circular polarizations. Since octave bandwidth isolators are not available at frequencies below 4 GHz bands, 1-2 GHz and 2-4 GHz amplifiers are of balanced design to allow for the input return loss of about 15 dB.

Figure 4. JVLA amplifiers: from left 38-50 GHz, 8-12 GHz, 4-8 GHz and 2-4 GHz are shown.

A typical noise and gain characteristics of the balanced 2-4 GHz amplifier measured at 15 K ambient temperature are shown in Fig. 5. Each channel has two stages of amplification and "cryo3" devices with 200 micron gate periphery are employed. For ease of design devices with larger gate periphery would have been preferred. Unfortunately wider gate devices from "cryo3" might exhibit instabilities (both of dc and rf nature) of yet not determined nature. Therefore, building a large number of amplifiers with repeatable performance at cryogenic temperatures using these devices would have been difficult. Concerns of cost, physical size and mechanical integrity upon cooling prompted the choice of a commercial LTCC hybrid (Anaren-Xinger series). This hybrid exhibits somewhat higher losses than possibly achievable in a custom design [15], resulting in penalty in noise performance. For this design, the cumulative contribution of ohmic losses to the amplifier noise performance exceeds 1.5 K. Very similar concerns governed design of 1-2 GHz amplifiers.

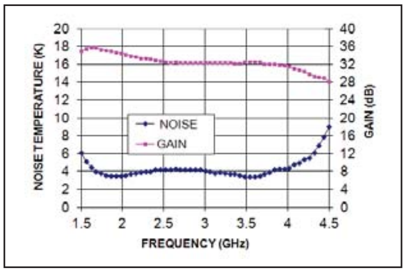

Figure 5. Gain of and noise characteristics measured at 15 K for JVLA 2-4 GHz amplifier. IRL is typically 15 dB for the whole frequency range.

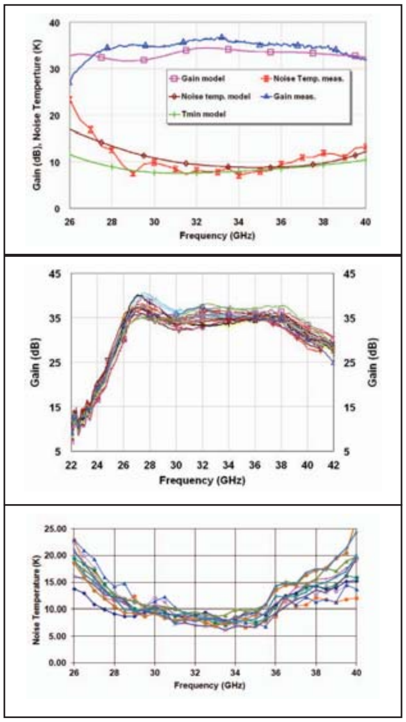

Figure 6. Measured and modeled characteristics of 26-40 GHz amplifiers at T_a=20 K: comparison of measured and modeled gain and noise temperature (top), gain measured on a sample of amplifiers (middle), noise temperature measured on a sample of amplifiers.

For amplifiers with waveguide inputs, the contribution of losses to the measured noise temperatures is relatively small compared to that in coaxial amplifiers and is comparable with typical errors encountered in noise measurements. Very low loss circuits preceding a first stage device in all the designs consist only of a waveguide probe, a short section of copper clad pure Teflon substrate, and a bias circuit using gold bond wires as transmission lines. The general approach to both the design and manufacturing followed that developed for

Wilkinson Microwave Anisotropy Probe (WMAP) amplifiers [7].

As an example, the characteristics of 26-40 GHz amplifiers are shown in Fig. 6. In this design, 80 micron wide “cryo3” HFETs were used in the first and second stages while the gain stages employed devices used during WMAP project [7]. The amplifier model was developed using the HFET equivalent circuit of Fig. 2, with the appropriate parasitic elements added. The noise and gain characteristics of sub-sets of over 70 amplifiers produced are also shown demonstrating the repeatability of performance at cryogenic temperatures that is practically achievable using conventional chip and wire technology.

The repeatability of performance of other JVLA amplifiers, of which more than 600 were built and already installed in the field, is quite similar.

V. CONCULDING REMARKS

Radio astronomy arrays of different types operating at centimeter and millimeter wavelengths typically require hundreds of ultra low noise receivers. A figure of merit might be the ratio of effective collecting area A_{eff} to the system noise temperature T_{sys} or, in case of surveys, A_{eff}/T_{sys}^2. The cost of A_{eff} for imaging arrays runs from tens to hundreds millions (and more) of US dollars and therefore reducing $T_{sys}=T_{ant}+T_{rcvr}$ is the most cost effective way of increasing scientific return or reducing instrument cost. For example in case of surveys 10 percent improvement in system noise results in 20 percent less collecting area for the same science outcome. As antennas are looking at mostly very cold sky (2.725 K of cosmic microwave background radiation modified by the presence of atmosphere), this practically always imposes the requirement of cryogenic cooling of receivers. Yet, even today, InP HFETs and similar technologies have not been able to consistently reproduce noise performance at cryogenic temperatures which stymied to a large extent the broad adaption of low noise MMIC’s for applications at cryogenic temperatures. Surprisingly very little research effort has gone into unraveling the underlying causes and even today some esoteric behaviors of “cryo3” devices, arguably best studied wafers so far, defy explanation. The successful design, prototyping and production of hundreds JVLA amplifiers described in this paper serve as an example that very mature, if not old fashioned, technology coupled with a careful evaluation of devices from a small set of wafers might offer a competitive solution, both on cost and performance, to advanced modern technologies. It is observed that the minimum noise measures of HFET technologies separated by more than a decade of development differ by very little, if at all. This observation underscores the importance of understanding the limits of noise performance of InP HFETs, especially with respect to further scaling of gate length.

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