MMA Memo 222:

CHARACTERISTICS OF BROADBAND INP HFET MILLIMETER-WAVE AMPLIFIERS AND THEIR APPLICATIONS IN RADIO ASTRONOMY RECEIVERS(1)

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Abstract--*Recent developments in ultra-low-noise, cryogenically-cooled, heterostructure field-effect transistor (HFET's) receivers for frequencies up to 110 GHz are reviewed. Design and examples of the realization of InP HFET receivers in the frequency range 18 to 110 GHz are described. Applications to ultra-low-noise radio astronomy receivers, as well as broadband continuum radiometers, are discussed.*

Keywords: field-effect transistor, high-electron-mobility transistor, heterostructure field-effect transistor, noise, noise modeling, low-noise amplifiers, radiometers, radio astronomy

1. INTRODUCTION

In the early 1970's, the ultra-low-noise receiving systems employed mainly solid-state masers, cryogenically-cooled parametric amplifiers (or converters) and Schottky diode mixers. At the end of that decade, the advances in the technology of GaAs FET's, combined with cryogenic cooling, made the noise performance of GaAs FET amplifiers competitive with the performance of parametric amplifiers [1], [2]. Also, a new mixing element, superconductor-insulator-superconductor (SIS) junction, capable of quantum limited detection, was developed [3]-[5].

The progress in the performance of FET and HFET amplifiers was quite dramatic: from state-of-the-art noise temperature of 20 K at 4.75 GHz in 1980 [1] to the state-of-the-art noise temperature of 15 K at 43 GHz in 1993 [6] at the ambient temperature of 18 K. This last result was achieved with InP lattice matched HFET's. Since 1993 the progress in the noise performance has not been significant. However, the technology of InP devices has matured and allowed for system insertion. The hybrid "chip and wire" amplifiers have been demonstrated up to frequencies of 110 GHz and successfully used in several instruments for radio astronomy research. These include: Very Large Array (VLA), Very Large Baseline Array (VLBA), Microwave Anisotropy Probe (MAP) and several ground-based instruments for the investigation of cosmic microwave background. A number of MMIC designs were demonstrated up to 140 GHz (for example, [16]) with even higher frequencies under development. In radio astronomy instrumentation, HFET receivers now compete in performance with masers and SIS mixer/HFET IF amplifier tandems for frequencies below 120 GHz. At frequencies above 120 GHz up to about 1 THz, SIS mixers demonstrate the best noise performance. Above 1 THz, cooled Schottky diode mixers and hot electron bolometer (HEB) mixers provide the lowest noise temperatures [8].

2. LOW-NOISE HFET'S: STATE-OF-THE-ART

For years, device technologists in their quest for low-noise FET (HFET) were guided by the relation developed by Fukui [10].

$$T_{min} \approx T_o K_f \frac{f}{f_T}\sqrt{g_m (r_g + r_s)}$$

(1)

where T_{min} is the minimum noise temperature, f is the frequency, T_o is the standard temperature 290 K, f_T is the intrinsic cut-off frequency, g_m is the transconductance, r_g and r_s are gate and source parasitic resistances, respectively, and K_f is the fitting factor, assuming values between 1.2 and 2.5. A corresponding approximate expression for the minimum noise temperature of a FET chip, based on the noise model developed by the author [11], can be written as:

$$T_{min} \approx 2 \frac{f}{f_T}\sqrt{r_t T_g g_{ds} T_d}$$

(2)

where T_g and T_d are equivalent gate and drain temperatures, respectively; g_{ds} is the drain-to-source conductance; and $r_t = r_s + r_g + r_{gs}$, where r_{gs} is the intrinsic gate resistance. T_g is approximately equal to the physical temperature T_a of a device.

The comparison of both expressions demonstrates that the technological progress towards increasing the values of f_T and reducing the values of r_g and r_s would result in lower noise temperatures (noise figures) as explained by both. The open question is whether the improvements in the noise performance of HFET's, be it conventional, pseudomorphic or lattice-matched, were only a consequence of increased values of intrinsic cut-off frequencies and reduced values of parasitic resistances, or were they also a result of the reduced value of the product T_d g_{ds} at optimal bias conditions [9].

It is well known that the minimum noise figure of a multistage amplifier with sufficient gain is determined not only by the device noise figure, but also by its associated gain. A more proper figure of merit is the minimum noise measure which determines the lowest noise temperature (noise figure) of an amplifier made of an infinite number of stages. It is, therefore, a very useful tool in establishing the limits of performance of practical amplifiers. An example of the dependence of minimum noise temperature M_{min} versus frequency for the state-of-the-art AlInAs/GaInAs/InP HFET's is shown in Fig. 1 [13]- [16].

3. DESIGN AND PERFORMANCE OF LOW-NOISE, MILLIMETER-WAVE CRYOGENIC AMPLIFIERS

Design of cryogenically-coolable amplifiers requires knowledge of the signal and noise properties of FET's at cryogenic temperatures. In one of the first studies of cryogenic properties of GaAs FET's [19], it was observed that the changes in the measured S-parameters upon cryogenic cooling could be mostly explained by the changes in the device transconductance g_m and drain-to-source conductance g_{ds}. A large number of later papers devoted to the investigation of the signal and noise properties of FET's and HFET's at cryogenic temperatures confirm this early observation (for example, [6], [7], [11], [12], [17]-[22]).

This observation, together with the noise model of [11], provide sufficient information to allow for computer-aided design of cryogenic amplifiers with optimal, according to some criterion, noise bandwidth performance. The criterion could be different for different applications: for example, minimum value of the maximum noise temperature across a given bandwidth, minimum value of the average noise temperature over a given bandwidth, etc. Usually an amplifier has to satisfy other requirements, as the input and output return loss, unconditional stability, minimum gain and gain flatness, etc., which can also be reliably investigated in a CAD process. As a result, there are no "set-in-stone" design rules; yet the following observations could prove valuable. In similarity with an impedance matching, the "noise matching" of a FET can be done perfectly only at a single frequency. Consequently, wideband "noise matching" is similar to wideband matching of a complex impedance to a resistive load. For a given frequency range, there is a particular gate width of a FET (HFET) which allows for the largest possible relative bandwidth. A proper choice of the inductance in series with the gate (for example, the inductance of the gate bond wire) usually results in the simplest broadband "noise matching" network. Also, a proper value of the source inductance allows one to address other requirements (stability, input return loss, gain flatness) without penalty in the noise temperature of a multistage amplifier.

The NRAO Central Development Laboratory has developed a number of InP HFET millimeter-wave amplifiers in the 18 to 110 GHz range for applications in radio astronomy receiving systems [6], [7], [17], [18], [27], [28].

An example of noise and gain characteristics and the comparison with the model prediction for a room temperature InP HFET, six-stage, W-band amplifier is shown in Fig. 2. The devices have gate dimension .1 x 50 m and are biased at V_{ds} = 1.0 V and I_{ds} = 5 mA. For the purpose of modeling, the equivalent circuit given in [17] is used. The noise model of [11] is assumed for noise computation with T_g = 297 K and T_d = 1500 K. All other resistors and lossy lines (1.7 dB/inch at 75 GHz) are assumed to be at T_a = 297 K. An example of noise and gain characteristics and the comparison with the model prediction for a cryogenic amplifier is shown in Fig. 3. The transistors were biased at V_{ds} = .9 V and I_{ds} = 3 mA in the first two stages and I_{ds} = 5 mA in the last three stages. For the model data, the only changes from room temperature were: $T_g = T_a$ = 27 K and T_d = 500 K and about 20% increase in transconductance g_m.

A summary of noise performance of HFET receivers cooled to approximately 20 K and a comparison with typical performance of SIS mixer receivers cooled to 4 K is presented in Fig. 4. Fig. 4 also shows the best performance of InP HFET receivers expected at any frequency for current state-of-the-art devices. This graph is based on minimum noise measure of a state-of-the-art, .1 µm gate length InP HFET, shown in Fig. 1, and includes a modest correction to the receiver noise temperature estimated from typical losses of matching circuits, waveguides, horns, dewar windows, etc. A broadband HFET receiver design can attain the noise temperature equal to the minimum noise measure only at a single frequency, a property clearly illustrated in Fig. 4. The examples of HFET receiver noise temperature, shown in Fig. 4, demonstrate that for a typical rectangular waveguide bandwidth, the average noise temperature is approximately equal to the value determined by the minimum noise measure at the highest frequency within the band.

The detailed characteristics of many of the amplifiers used in the construction of the laboratory receivers of Figure 4 will be discussed during presentation. This discussion will include examples of complex gain match over a waveguide band frequency range. For example, a gain match of ± 2.5 dB and a phase match of ± 25 degrees can be routinely obtained in NRAO hybrid designs at W-band.

4. RECEIVERS FOR RADIO ASTRONOMY

The general concept of a compact, HFET receiver for radio astronomy application has been outlined by Weinreb *et al.*[22] and several examples are given therein. The noise temperature of state-of-the-art receivers versus frequency can be estimated from the data shown in Fig. 4. In the examples of Fig. 4, only the noise contribution of a dewar window and that of a horn at cryogenic temperature are responsible for the difference between the amplifier and receiver noise temperature. In practical receivers, an addition of different other components (polarizer, orthomode transducer (OMT), hybrids, circuits for the injection of the calibration signals) may be needed. These, depending on their physical temperature, may further degrade the performance of the systems, both in noise and bandwidth.

Recently, the modest cooling requirements, large instantaneous bandwidth, and very low noise of HFET millimeter-wave amplifiers have spurred the interest in their use as broadband continuum radiation detectors, especially for cosmic microwave background radiation measurements (for example, [23], [24]). The radiometric sensitivity of such receivers may be limited by random gain fluctuations of broadband HFET amplifiers.

By design, the voltage response of a radiometer in the Rayleigh-Jeans limit is a linear function of the incident noise power

$$V_{dc} = (k_b T_{sys} \Delta\nu_{rf}) G_{rf} G_{video} R$$

(3)

where k_b 1.4 x 10^{-23} J/K, T_{sys} is the system temperature (the sum of the receiver and antenna noise temperatures), and $_{rf}$ is the effective RF bandwidth. Sufficient RF gain and detector responsivity must be present for the first-stage noise to dominate the contributions from the square-law detector, with responsivity R, and subsequent post-detection electronics.

In the presence of gain fluctuations, the following parameterization for the radiometer's spectral density V (in Volts/rt-Hz) may be employed:

$$\frac{\delta V}{V_{dc}} = \frac{\delta T}{T_{sys}} = \kappa_0 \left(\frac{2}{\Delta \nu_{rf}} + \left(\frac{\Delta T_{offset}}{T_{sys}} \right)^2 \delta g^2(f) \right)^{1/2} ,$$

(4)

where $_0$ is the demodulation efficiency and $g^2(f)$ is the radiometer's total noise spectral density of the gain fluctuations as a function of video frequency. A simple power law dependence with frequency is observed for the gain fluctuation in HEMT's $g^2(f)$ (1 Hz/f) where g^2 is the amplitude and 0.9 is the spectral index of the spectral density [25]. After calibration, it is convenient to express the sensitivity in terms of the spectral noise density T in mK/rt-Hz.

For a direct detection receiver, $_0$ = 1. From (4), one notes for such a receiver in the narrow bandwidth limit, the ratio of spectral density to the mean signal output approaches a constant magnitude $\delta V / V_{dc} = \sqrt{2/\Delta \nu_{rf}}$. In the wide bandwidth limit, the radiometric offset and gain stability determine the effective spectral density V/V_{dc} = (1Hz/f) $^{/2}$ g. The so-called "knee" or "corner" frequency f_{knee} ~ $(_{rf}g^2/2)^{1/}$, occurs at the transition between these two regions.

An example of the output power spectra of a radiometer built with amplifiers similar to those of Figs. 2, 3 and 4 is shown in Fig. 5. The largest bandwidth of this radiometer was 20 GHz, but smaller bandwidth could be selected by bandpass filters (comp. Fig. 5). The system temperature was measured with a feed horn viewing a hot/cold load through a mylar vacuum window. The measured receiver noise was 300 ± 10 K at room temperature and 80 ± 10 K when cooled to a physical temperature of 50 K. The measured receiver sensitivity was 3 mK/rt-Hz at an ambient temperature of 300 K and 0.8 mK/rt-Hz at 50 K for video frequencies >> 10 kHz and an effective RF bandwidth of 20 GHz. For both bandwidths, 3 GHz and 20 GHz , the noise at a video frequency of 100 kHz was within ~ 5% of the magnitude computed from the measured system temperature and effective bandwidth. The measured sensitivities at room temperature are the best reported for a continuum receiver in the 3 mm atmospheric window. At 50 K, the observed receiver sensitivity is competitive with the cryogenic performance of sub-Kelvin bolometric detectors or SIS mixers with a wideband IF. Obviously, the sensitivities limited by bandwidth and the system noise temperature can be attained only in a proper receiver design, as, for example, Dicke receiver with sufficiently fast switching, correlation receiver, etc. [23]-[27].

5. ACKNOWLEDGMENTS

The contributions of L. Nguyen of Hughes Research Labs, and J. Webber, A. R. Kerr, S.-K. Pan, N. Bailey, S. Thacker, W. Lakatosh, W. Wireman, R. Harris of NRAO are gratefully acknowledged.

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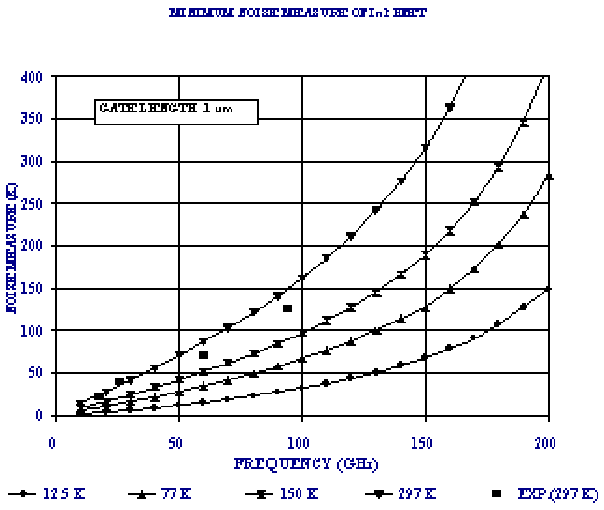

Fig. 1. A minimum noise measure of a .1 m gate length AlInAs/GaInAs/InP HFET. Experimental results at room temperature from three different laboratories are also shown: "" [13]-[16].

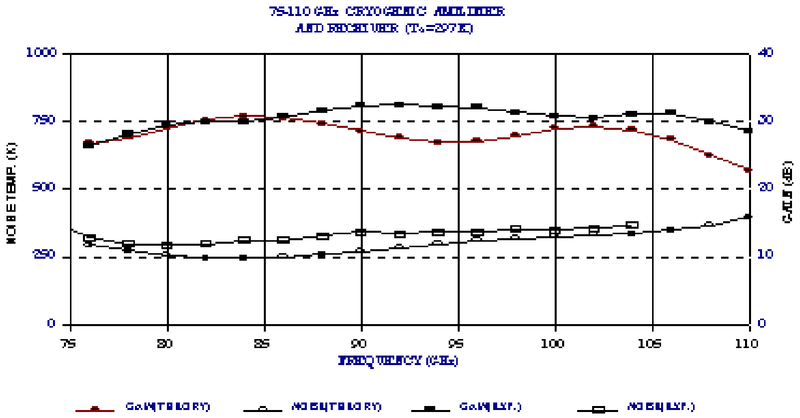

Fig. 2. A comparison of measured gain and noise characteristics of a W-band amplifier with model prediction at room temperature. Measured noise includes the contribution of pyramidal horn and receiver (T_n 2000 K).

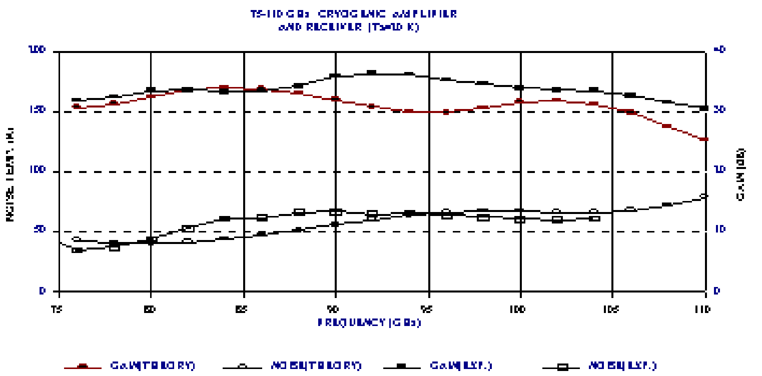

Fig. 3. A comparison of measured gain and noise characteristics of a W-band amplifier with model prediction at cryogenic temperature (T_a = 20 K). Measured noise temperature includes the contribution of dewar window, pyramidal horn (T_a = 20 K) and room temperature receiver (T_n 2000 K).

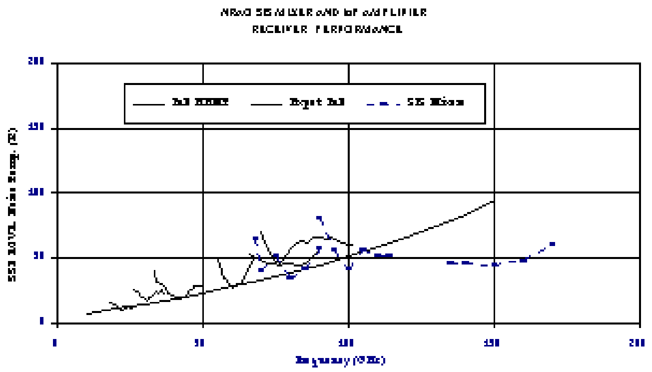

Fig. 4. Comparison of noise temperature of NRAO cryogenic receivers using InP HEMT amplifiers cooled to about 20 K and SIS mixer receivers cooled to 4 K (SIS mixer receiver data courtesy of A. R. Kerr and S.-K. Pan, NRAO).

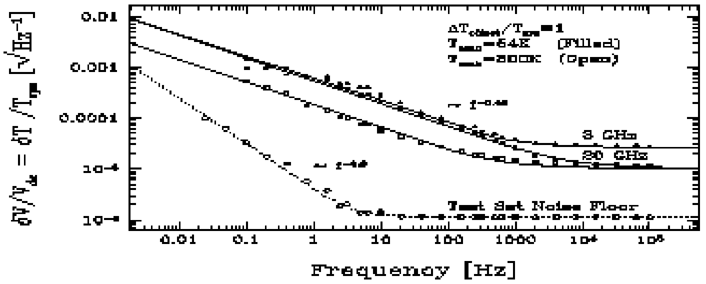

Fig. 5. The power spectra of the radiometer output. The filled symbol data were taken at a physical temperature of 54 K and the indicated effective RF bandwidths. The open symbol data were taken at a physical temperature

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1. An earlier version of this paper was presented at the 1997 Topical Symp. on Millimeter-Wave, Shonan Village, Japan, July 1997.

2. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.