CRYOGENICALLY-COOLED, HFET AMPLIFIERS AND RECEIVERS: STATE-OF-THE-ART AND FUTURE TRENDS

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ABSTRACT

Recent progress in the development of ultra-low-noise, cryogenically-coolable, HFET (heterostructure field-effect transistor) amplifiers and receivers for radio astronomy applications is reported.

Examples of state-of-the-art receivers at frequencies from L- to Q-band are discussed. A model-based prediction of future performance demonstrates that HFET receivers should soon be competitive with SIS mixer receivers at W-band frequencies.

INTRODUCTION

A simple wideband noise model of a field-effect transistor introduced in recent papers [1]-[3] allows for the design of cryogenic amplifiers with optimized noise performance over a given frequency bandwidth [4], [5], [7]. As a result, the realization of the low-noise radio astronomy receivers having "optimal," within other design constraints, noise bandwidth performance becomes possible.

This paper presents first a review of the performance of a family of cryogenically-coolable amplifiers developed at the NRAO Central Development Laboratory in the 1 to 50 GHz range and then a review of the performance of receivers employing these amplifiers.

Finally, several observations are offered concerning the current state and future trends in the development of cryogenically-coolable HFET receivers.

HFET AMPLIFIERS

A summary of the typical performance of NRAO cryogenic HFET amplifiers is presented in Figure 1. The noise temperature data are referred to the cold input of the amplifiers [4], [5], [7]. The noise performance of these amplifiers is plotted with the minimum noise measure of the FHR02X HEMT, a quarter-micron gate device available from Fujitsu [6]. Also, the noise temperature of the 38-45 GHz amplifier is plotted with the minimum noise measure of the .1 μm gate PHFET device from ROHM Research [8], [9]. The data for the 4 K masers [10]-[12] are given for comparison. The amplifier examples demonstrate that for a bandwidth of around an octave or less the amplifier average noise temperature T_{nav} is approximately equal to the minimum noise measure M_{min} at the highest frequency within the band:

$$T_{nav} = \frac{1}{f_{max} - f_{min}} \int_{f_{min}}^{f_{max}} T_n \, df \approx M_{min}(f_{max})$$

An excellent agreement between predicted and measured noise performance of the amplifiers [4], [5], [7] both at room and cryogenic temperatures, was a result of the development of a FET noise model [1]-[3]. This model allows also for a reasonable prediction of future performance. A minimum noise measure vs. frequency of a "futuristic" cryogenic HFET is presented in Figure 2 for different ambient temperatures. A model of this device was created by assigning to the equivalent circuit of a current experimental HFET [13] the values of equivalent gate and drain temperatures (which determine the noise properties of a device) typical of the best devices currently in use (the equivalent gate temperature equal to the ambient temperature and the equivalent drain temperature equal to 1000 K and 400 K at ambient temperature of 297 K and 12.5 K, respectively). The "futuristic" device under consideration was the .15 μm long gate HFET using AlInGa/GaInAs on an InP wafer structure from GE [13]. The published room temperature noise measure data of GE devices [13] fit extremely well the model prediction, as do the data from Hughes and TRW on similar devices [14], [15]. The data for this device at other ambient temperatures were obtained under the assumption that the equivalent gate and drain temperatures behave like those for .1 μm ROHM Research HFET [8], [9] routinely used at NRAO. Therefore, the term "futuristic" used for this device reflects only an uncertainty about its cryogenic performance.

RECEIVERS

The general concept of a compact, low-noise, HFET receiver for radio astronomy applications has

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been outlined by Weinreb, *et al.* [16] and several examples are given therein. The examples of performance of wideband designs are shown in Figures 3 and 4 for K_u- and Q-band, respectively. The K_u-band results demonstrate clearly that the receiver performance is limited, both in terms of noise and bandwidth, by the components placed ahead of the amplifier. In this particular case, the noise degradation is due to the cumulative losses of window, polarizer, coupler, isolator and connecting cables while the bandwidth is limited by the polarizer and isolator.

The performance of the Q-band receiver [18] is the best yet reported for HFET receivers and is comparable in performance to SIS mixer receivers built for this frequency range. The noise temperature of the receiver is determined by the cryogenic amplifier noise temperature ($\leq$ 30 K) and the losses of waveguide components (polarizer, coupler, isolator) preceding the amplifier.

Further improvements are possible if the expected cryogenic performance of AlInAs/GaInAs on InP HFET's is confirmed experimentally. A comparison of NRAO HFET receivers and SIS receivers [17] is shown in Figure 5. The expected performance of HFET receivers built with current experimental devices is also shown, illustrating that their performance should soon be competitive with SIS receivers at 3 mm wavelengths.

CONCLUSIONS

The trade-off in low-noise amplifier design (bandwidth, input VSWR, stability, gain) can be reliably investigated in a computer model leading to the design with an "optimal" noise bandwidth performance. The bandwidth of a receiver is no longer limited by the amplifier bandwidth. In many receiving systems, the noise of a HFET amplifier is no longer a dominant contribution to the system noise. The Q-band HEMT receiver demonstrates the performance competitive with that of SIS/HEMT IF receivers. It is expected that wide bandwidth HEMT receivers will compete with SIS/HEMT IF receivers at 100 GHz.

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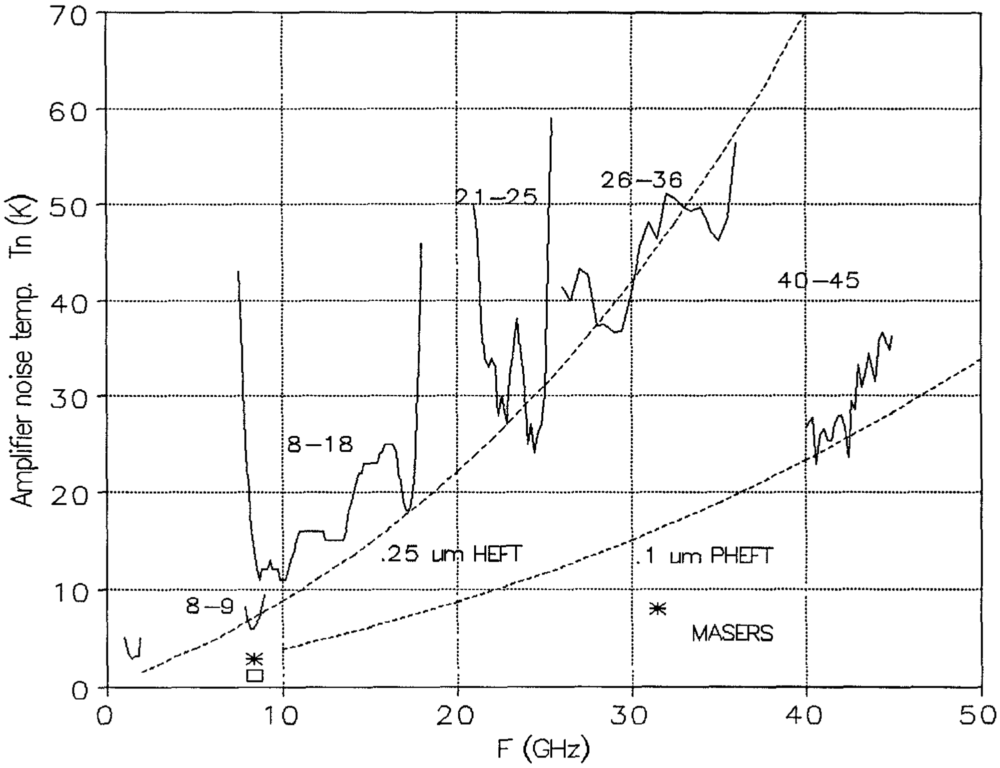

Fig. 1. Noise temperature of different amplifiers and minimum noise measure of FHR02X (.25 μm gate length) and H-CF-100-6 (.1 μm gate length) at $T_a = 12.5$ K. The noise performance of masers at 4 K and 1.9 K (a lower point at 8.4 GHz) is also shown for comparison.

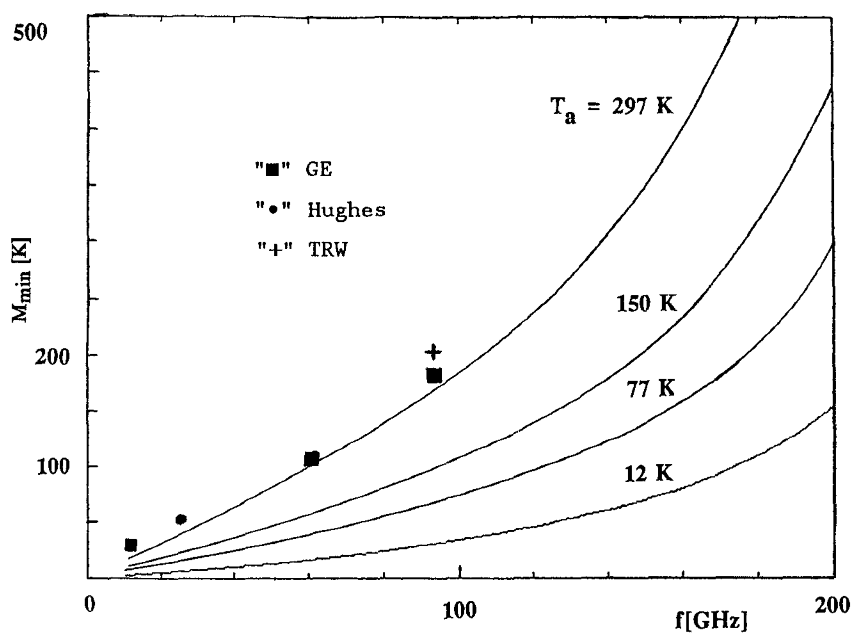

Fig. 2. A minimum noise measure of a "futuristic" HFET. Experimental results at room temperature for AlInAs/GaInAs on InP HFET's from three different laboratories are also shown: "■" GE [13], "•" Hughes [14], "+" TRW [15].

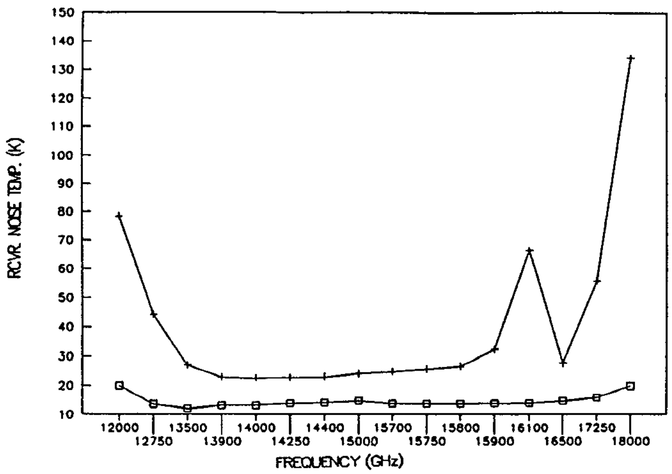

Fig. 3. Noise performance of cryogenic K_u-band amplifier (□) and receiver (+).

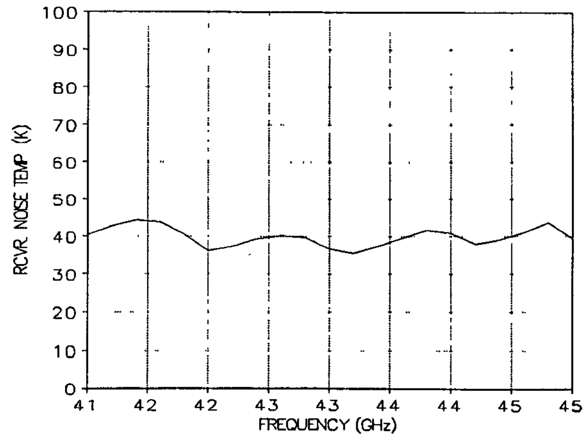

Fig. 4. Noise performance of the Q-band receiver (courtesy of R. Norrod and M. Masterman [18]).

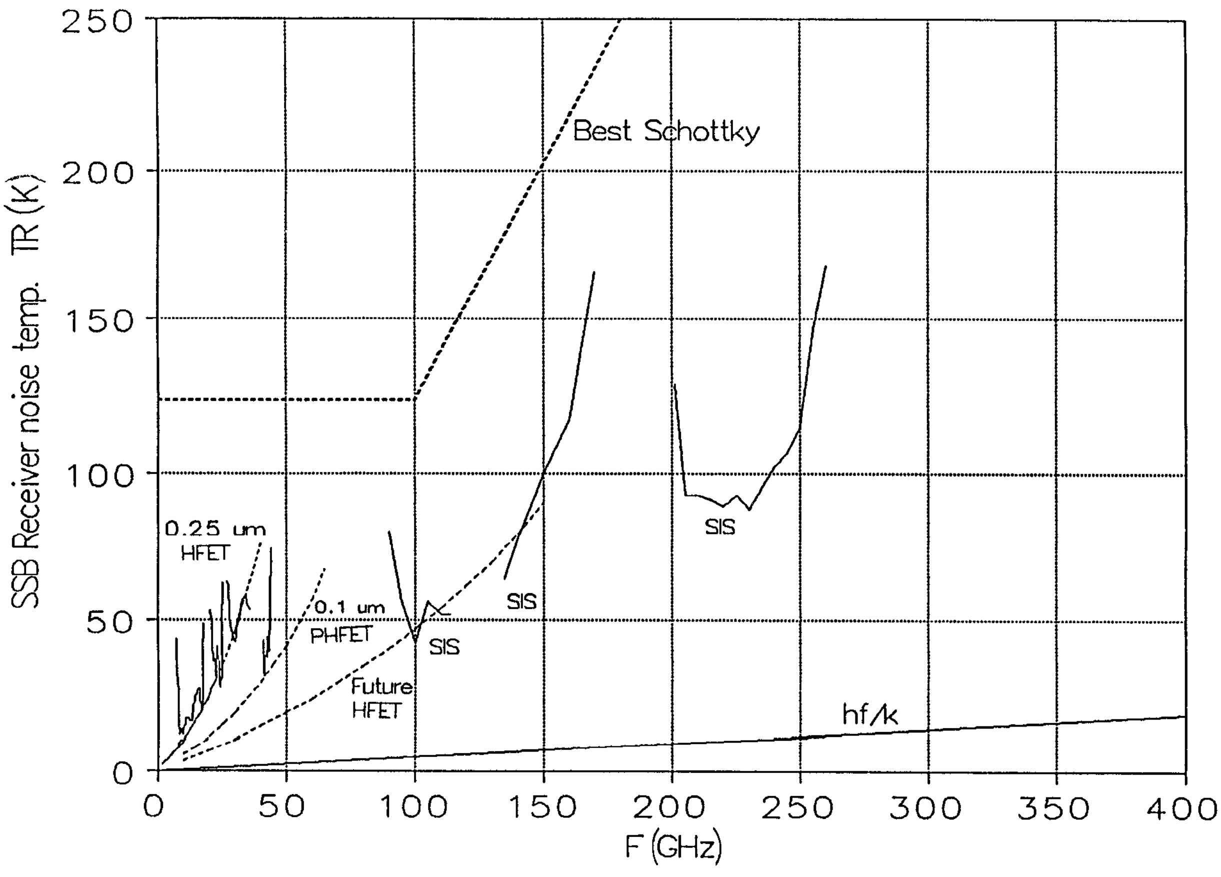

Fig. 5. A comparison of NRAO HFET and SIS receiver performance (SIS and Schottky mixer data courtesy of A. R. Kerr and S.-K. Pan [17]) with that expected from the current experimental devices ("future HFET's").