MILLIMETER-WAVE WAVEGUIDE-BANDWIDTH CRYOGENICALLY-COOLABLE InP HEMT AMPLIFIERS

M. W. Pospieszalski, W. J. Lakatosh, E. Wollack
National Radio Astronomy Observatory*
Charlottesville, VA 22903

Loi D. Nguyen, Minh Le, Mark Lui, Takyiu Liu
Hughes Research Labs
Malibu, CA 90625

ABSTRACT

The design, construction and performance of 65-90 GHz and 75-110 GHz low-noise cryogenically-coolable amplifiers are presented. A comparison between modeled and measured performance is shown. A laboratory receiver exhibiting an average noise of 50 K across 65-90 GHz and 70 K across 75-110 GHz is described. These are the widest band and lowest noise HEMT receivers ever reported at these frequencies.

INTRODUCTION

InP-based high-electron mobility transistors, cooled to cryogenic temperatures, have for several years held a promise of allowing the construction of full waveguide bandwidth millimeter-wave receivers with noise performance comparable with SIS mixer receivers [1]. The noise performance of 50 K at 100 GHz was predicted in 1992 for a cryogenic HEMT receiver [1]. Since then several "progress reports" toward this goal were published [2]-[4] which covered the cryogenic performance of state-of-the-art InP HEMT's. This paper presents the performance of amplifiers covering 65-90 GHz and 75-110 GHz in a laboratory receiver with noise performance of 50 K and 70 K, respectively. The more specific application of these amplifiers in a very sensitive continuum radiometer is reported in another paper [5].

DEVICE

The InP HEMT used in this study [6] consists of a 250-nm undoped AlInAs buffer, a 40-nm GaInAs channel, a 1.5-nm undoped spacer, an 8-nm AlInAs donor layer doped to approximately 7 x 10^{18} cm^{-3} and, finally, a 7-nm GaInAs doped cap, all grown lattice-matched to InP on a 2-inch semi-insulating substrate. Because of its simplicity, this particular HEMT structure has been chosen for most of Hughes' low-noise work in the past several years. It typically exhibits an electron sheet density of 2.5 to 2.8 x 10^{12} cm^{-2} and a room-temperature mobility of 10,000 to 11,000 cm^2/Vs.

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

The d.c. characteristics of a similar device, its equivalent circuit and noise parameters, both at room and cryogenic temperatures, were presented in [3] and [4]. The devices used in the 65-90 and 75-110 GHz amplifiers, although manufactured with the same technology as those described in [3] and [4], possess slightly different cryogenic properties. These differences follow similar patterns as those established for cryogenic performance of AlGaAs/GaAs HFET's [7]. In short, the differences are limited to the change in device behavior under illumination (about 18 percent improvement in noise temperature upon illumination for current devices) and also to the device performance for very small currents (close to the "pinch-off").

65-90 GHz and 75-110 GHz AMPLIFIERS

Both amplifiers were realized in hybrid technology using pure PTFE, 3-mill thick substrates. The choice of "chip and wire" technology was dictated not only by the objective of achieving the lowest possible noise performance, but also by the much lower cost than MMIC's, in relatively low volume radio astronomy applications.

A photograph of the 75-110 GHz five-stage amplifier is shown in Fig. 1. This amplifier uses full waveguide bandwidth, E-plane probe waveguide-to-microstrip transitions (IRL > 18 dB across the band). The input and first two interstage coupling networks were designed to achieve the lowest average noise temperature across the band while the last two interstage coupling networks were designed to achieve a flat gain across the band. The bias networks also use "chip and wire" technology with bond wires being treated as transmission lines in the design process. All the bias network elements having influence on millimeter-wave characteristics and coupling capacitors are manufactured using 5-mil thick quartz substrate.

An example of noise and gain characteristics and the comparison with the model prediction for a room temperature amplifier is shown in Fig. 2. The devices have gate dimension .1 x 50 μm and are biased at V_{ds} = 1.0 V and I_{ds} = 5 mA.

For the purpose of modeling, the equivalent circuit given in [4] 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.

0-7803-4603-6/97/$5.00 (c) IEEE

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: g_m = 50 ms (I_{ds} = 3 mA), g_m = 60 ms (I_{ds} = 5 mA), $T_g = T_a$ = 27 K and T_d = 500K. It is interesting to note that the values of equivalent drain temperature T_d explaining the measured data are the same as given in Fig. 4 of reference [4].

An example of the gain dependence of a W-band amplifier vs. ambient temperature under different biasing schemes, constant current or constant gate voltage, is shown in Fig. 4.

Constant current refers to all stages being biased at V_{ds} = 1.0 V, I_{ds} = 5 mA. A plot of a gate voltage required to satisfy this condition for one of the stages is also shown. Constant voltage refers to gate voltages being kept the same regardless of temperature. For the example shown in Fig. 4, the drain current changes typically from 5 mA at T_a = 297 K, to about 3 mA at 77 K, and to about 4 mA at T_a = 27 K.

The noise and gain characteristics of two cryogenic amplifiers showing a typical repeatability of performance for devices from the same wafer are shown in Fig. 5.

An example of the characteristics of a 65-90 GHz amplifier at cryogenic temperature and a comparison between measured and modeled results is shown in Fig. 6. In this design, an overriding objective was the minimum noise temperature which usually results in a gain decreasing across the band.

For both amplifiers, the noise temperature was measured in a receiver setting and no correction for the room temperature receiver ($T_n \simeq$ 2000 K), the pyramidal horn at cryogenic temperature and the dewar window was done.

CONCLUSIONS

The noise performance of InP HEMT cryogenic receivers is currently competitive with SIS mixer receivers in the 3-mm wavelength atmospheric window. A comparison of NRAO SIS receivers (600 MHz IF bandwidth) [8], [9] with HEMT cryogenic receivers is shown in Fig. 7. HEMT receivers offer an advantage of instantaneous coverage of full waveguide band, relaxed cooling requirements (15 K versus 4 K), and a very graceful degradation of noise temperature upon increase in ambient temperature. Shorter, self-aligned gate devices [10] offer a possibility of future improvements.

REFERENCES

[1] M. W. Pospieszalski, "Cryogenically-Cooled, HFET Amplifiers and Receivers: State-of-the-Art and Future Trends," (invited) *Proc. 1992 IEEE MTT-S Int. Microwave Symp.*, Albuquerque, NM, pp. 1369-1372, June 1992.

[2] M. W. Pospieszalski, W. J. Lakatosh, R. Lai, K. L. Tan, D. C. Streit, P. H. Liu, R. M. Dia, and J. Velebir, "Millimeter-Wave, Cryogenically-Coolable Amplifiers Using AlInAs/GaInAs/InP HEMT's," in *Proc. 1993 IEEE MTT-S Int. Microwave Symp.*, Atlanta, GA, pp. 515-518, June 1993.

3] M. W. Pospieszalski, L. D. Nguyen, M. Lui, T. Liu, M. A. Thompson and M. J. Delaney, "Very Low Noise and Low Power Operation of Cryogenic AlInAs/GaInAs/InP HFET'S," in *Proc. 1994 IEEE MTT-S Int. Microwave Symp.*, San Diego, CA, pp. 1345-1346, May 1994.

[4] M. W. Pospieszalski, W. J. Lakatosh, L. D. Nguyen, M. Lui, T. Liu, M. Le, M. A. Thompson and M. J. Delaney, "Q- and E-Band Cryogenically-Coolable Amplifiers Using AlInAs/GaInAs/InP HEMT's," in *Proc. 1995 IEEE MTT-S Int. Microwave Symp.*, Orlando, FL, pp. 1121-1124, May 1995.

[5] E. J. Wollack and M. W. Pospieszalski, "Characteristics of Broadband InP Millimeter-Wave Amplifiers for Continuum Radiometry," submitted for presentation, URSI Radio Science Meeting, July 1997.

[6] L. D. Nguyen *et al.*, "Manufacturability of 0.1-μm Millimeter-Wave Low-Noise InP HEMT's," in *Proc. 1993 IEEE MTT-S Int. Microwave Symp.*, pp. 345-347, Atlanta, GA, June 1993.

[7] K. H. G. Duh, M. W. Pospieszalski, W. F. Kopp, P. Ho, A. Jabra, P. C. Chao, P. M. Smith, L. F. Lester, J. M. Ballingall, and S. Weinreb, "Ultra Low-Noise, Cryogenic High-Electron-Mobility Transistors," *IEEE Trans. Electron Devices*, vol. ED-35, pp. 249-256, March 1988.

[8] A. R. Kerr and S.-K. Pan, "Some Recent Developments in the Design of SIS Mixers," *Int. J. Infrared & Millimeter Waves,* vol. 11, no. 10, pp. 1169-1187, October 1990.

[9] A. R. Kerr and S.-K. Pan, private communication.

[10] L. D. Nguyen *et al.*, "50-nm Self-Aligned Pseudomorphic AlInAs/GaInAs High Electron Mobility Transistors," *IEEE Trans. Electron Devices*, vol. 39, pp. 2007-2014, Sept. 1992.

[11] M. W. Pospieszalski, "Modeling of Noise Parameters of MESFET's and MODFET's and Their Frequency and Temperature Dependence," *IEEE Trans. on Microwave Theory and Tech.*, vol. MTT-37, pp. 1340-1350, Sept. 1989.

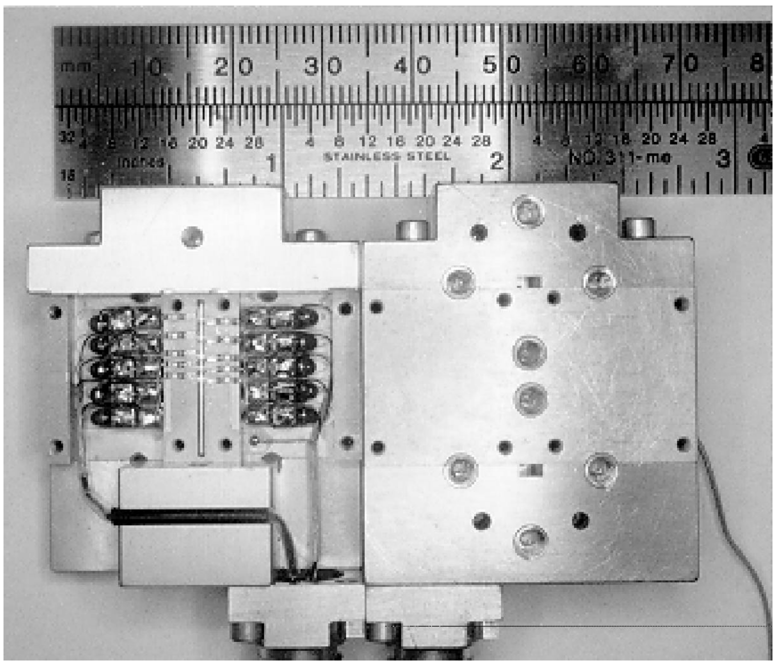

Fig. 1. A photograph of a 75-110 GHz amplifier with the cover plate removed.

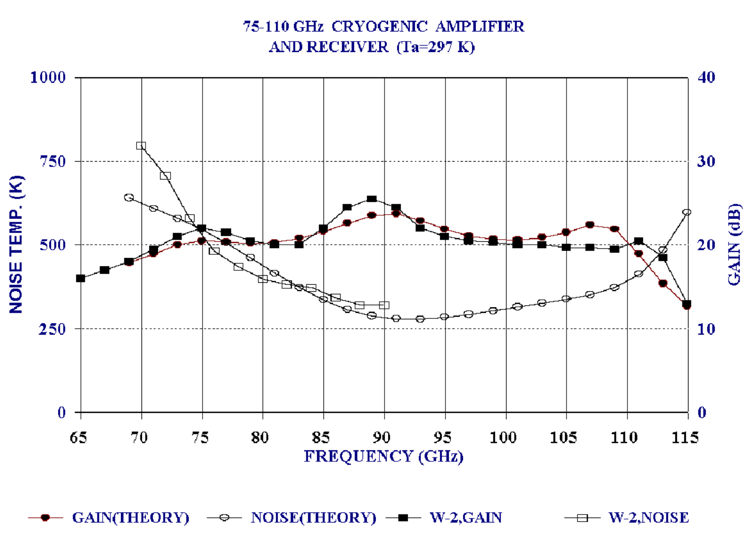

Fig. 2. A comparison of measured gain and noise characteristics of a W-band amplifier with model prediction at room temperature. Measured noise includes the contribution of pyramidal horn and receiver ($T_n \simeq$ 2000 K).

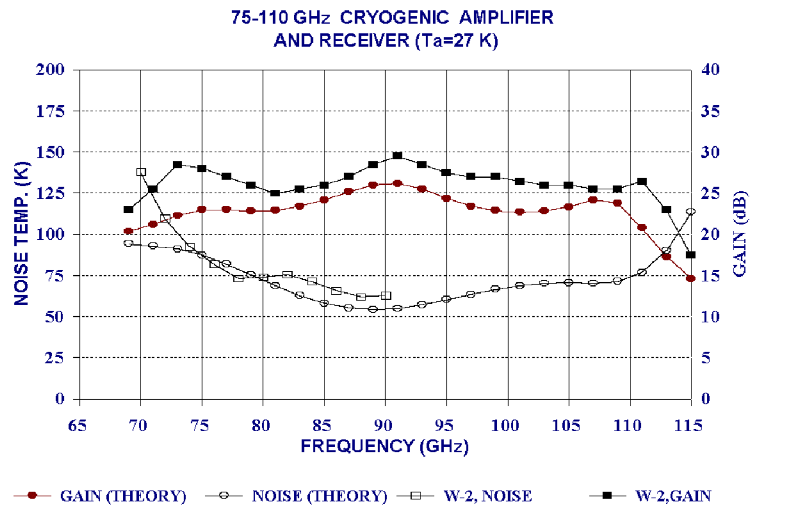

Fig. 3. A comparison of measured gain and noise characteristics of a W-band amplifier with model prediction at cryogenic temperature (T_a = 27 K). Measured noise temperature includes the contribution of dewar window, pyramidal horn (T_a = 27 K) and room temperature receiver ($T_n \simeq$ 2000 K).

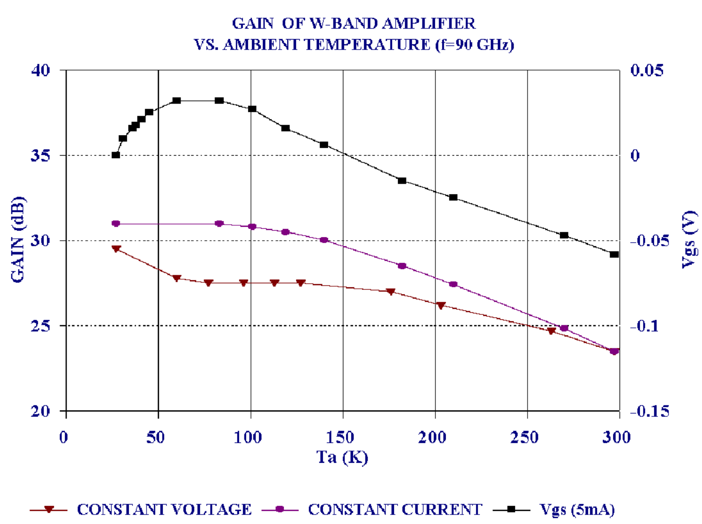

Fig. 4. Gain dependence of W-band amplifier at 90 GHz versus ambient temperature under different bias schemes. Constant current refers to all stages being biased at I_{ds} = 5 mA (a plot of gate voltage required to satisfy this condition is also plotted). Constant voltage refers to the gate voltages being kept constant regardless of temperature.

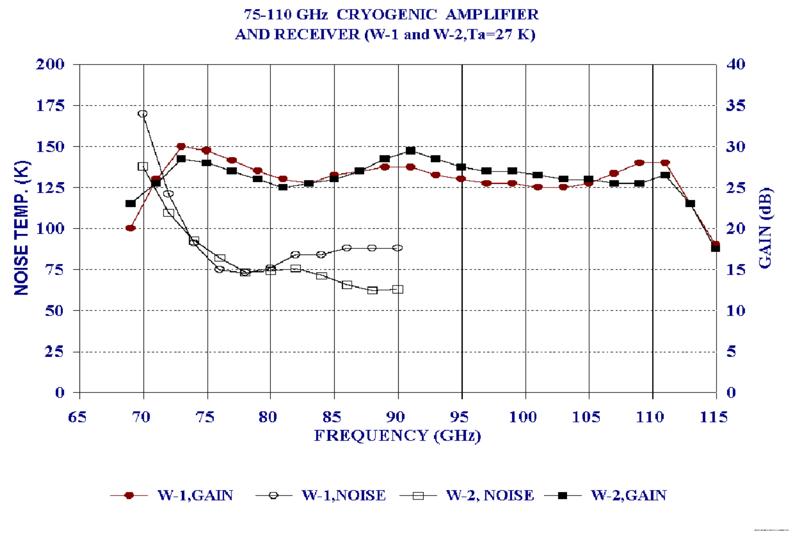

Fig. 5. Cryogenic (T_a = 27 K) gain and noise temperature characteristics of two 75-110 GHz amplifiers. Noise temperature includes the contribution of dewar window, pyramidal horn (T_a = 27 K) and room temperature receiver ($T_n \simeq$ 2000 K).

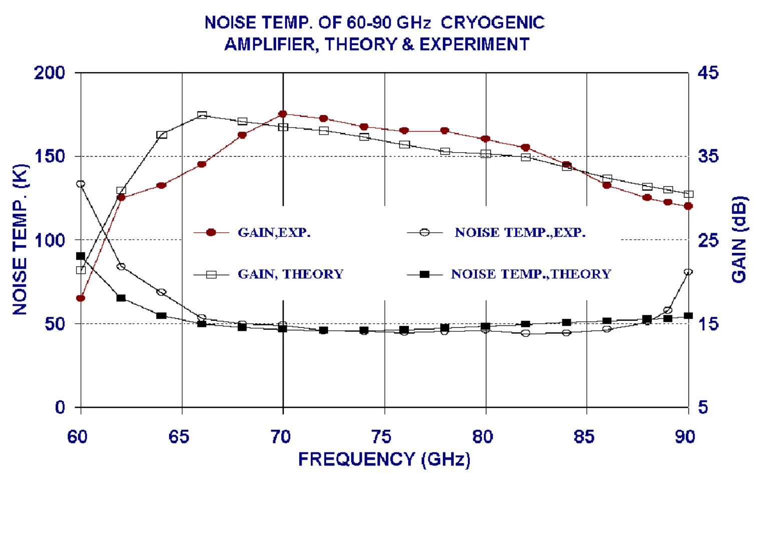

Fig. 6. Example of gain noise and performance of E-band cryogenic (T_a = 27 K) amplifier compared with model prediction. Noise temperature includes the contribution of dewar window, pyramidal horn (T_a = 27 K) and room temperature receiver ($T_n \simeq$ 2000 K).

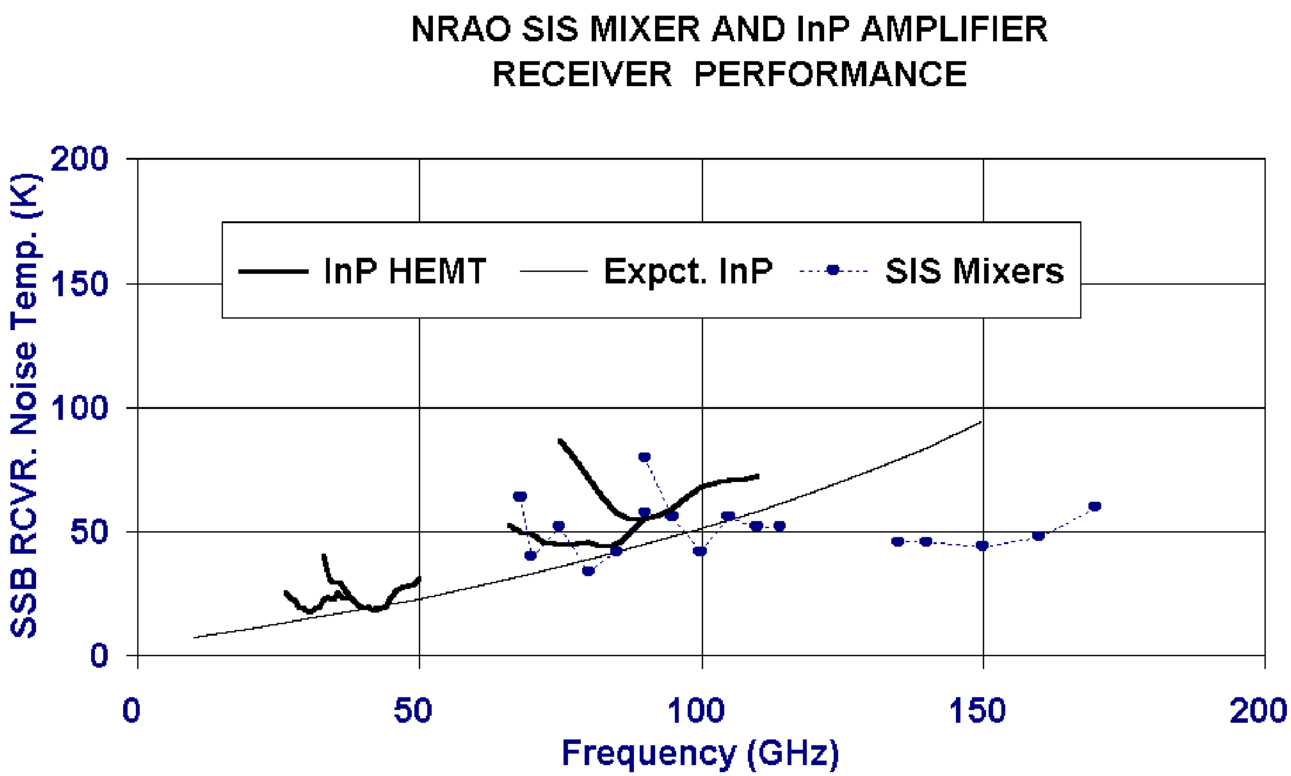

Fig. 7. Comparison of noise temperature of NRAO cryogenic receivers using InP HEMT amplifiers cooled to about 20 K and SIS mixer receivers (A. R. Kerr and S.-K. Pan) cooled to 4 K.